NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

OPTIMIZATION OF SURFACE SHIP STEERING
IN SEA STATE

by

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December 1984

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The model was tested in calm waters and sea states (regular and irregular) as well, for a certain speed and different encounter wave angles and encounter frequencies.

Also, an adaptive control was studied which updates the controller parameters while either the environmental conditions or the ship's steering characteristics change in order to maintain optimal steering performance.

Optimization of Surface Ship Steering in Sea State

by

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A computer model of the SL-7 containership along with a cascaded controller (one pole, one zero) were coupled to a function minimization subroutine and a sea state generator program. This scheme provided the appropriate controller parameters in order to accomplish the best performance.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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I. INTRODUCTION

The economics associated with ship operations have necessitated an examination of the losses associated with the motion of an automatically steered ship in a seaway.

Four major areas where fuel losses occur during the operation of a ship have been identified [Ref. 1, 2]. These areas on existing steam/diesel tankers are shown below:

- Power plant and auxiliaries
- Propeller efficiency
- Hull resistance
- Steering and navigation

An optimized autopilot design would provide effective steering control with associated cost savings due to reducing fuel consumption.

An appropriate computer model which represents the ship is necessary for studies leading to appropriate controller design. Chapter 2 introduces the development of two of these models.

Chapter 3 addresses the formulation of a performance criterion which represents the added drag due to steering of the ship.

Using the equations of motion as a model of the ship and a function minimization subroutine we proceed to the controller design for regular seas (deterministic model for the seaway) in Chapter 4, and for irregular seas (nondeterministic model) in Chapter 5. The function minimization subroutine used was BOXPLX and was programmed by R. R. Hilleary of the Naval Postgraduate School Computer Center [Ref. 3]. It will find the minimum of any arbitrary function, linear or nonlinear, subject to explicit constraints of the variables or implicit constraints on functions of the variables.

Chapter 6 introduces another function minimization subroutine appropriate for onboard use.

An adaptive control, which updates the controller parameters when the environmental conditions or the ship's course change, is studied in Chapter 7.

Conclusions drawn from these experiments and recommendations for future studies are addressed in Chapter 8.

II. COMPUTER MODELS OF THE SHIP

A nontrivial part of any control problem is modelling the process. Thus, an appropriate computer model which represents the ship is necessary. The best representation of the ship's steering dynamics is a Taylor's series expansion of the force and moment relationships around a selected steady state operating point. The equations obtained in this way are known as the equations of motion [Ref. 4], and the formulation in the computer program is indicated in Appendix A. This computer program was developed by using known available data for the SL-7 containership and by implementation of the scheme in Figure 2.1 [Ref. 5].

In this scheme the function minimization subroutine is fed by the yaw error ψ_e and rudder angle δ, computes the performance criterion J and adjusts the controller free parameters in order to minimize J.

A second model for the ship-steering dynamics representation is the Nomoto model. Figure 2.2 indicates the second and third order Nomoto transfer functions while Figure 2.3 indicates the appropriate scheme used for obtaining these models from the equations of motion. Appendix A includes the computer program used for the Nomoto third order model determination.

A yaw command is applied as input in the scheme in Figure 2.3 and the difference of the signals ψ_M and ψ_{EQ} is fed to the function minimization subroutine which attempts to adjust the free parameters of the Nomoto plant in order to minimize the performance criterion J.

Simulation runs indicate that the resulting Nomoto models are obtained with resulting J close to zero. However, in this study the equations of motion

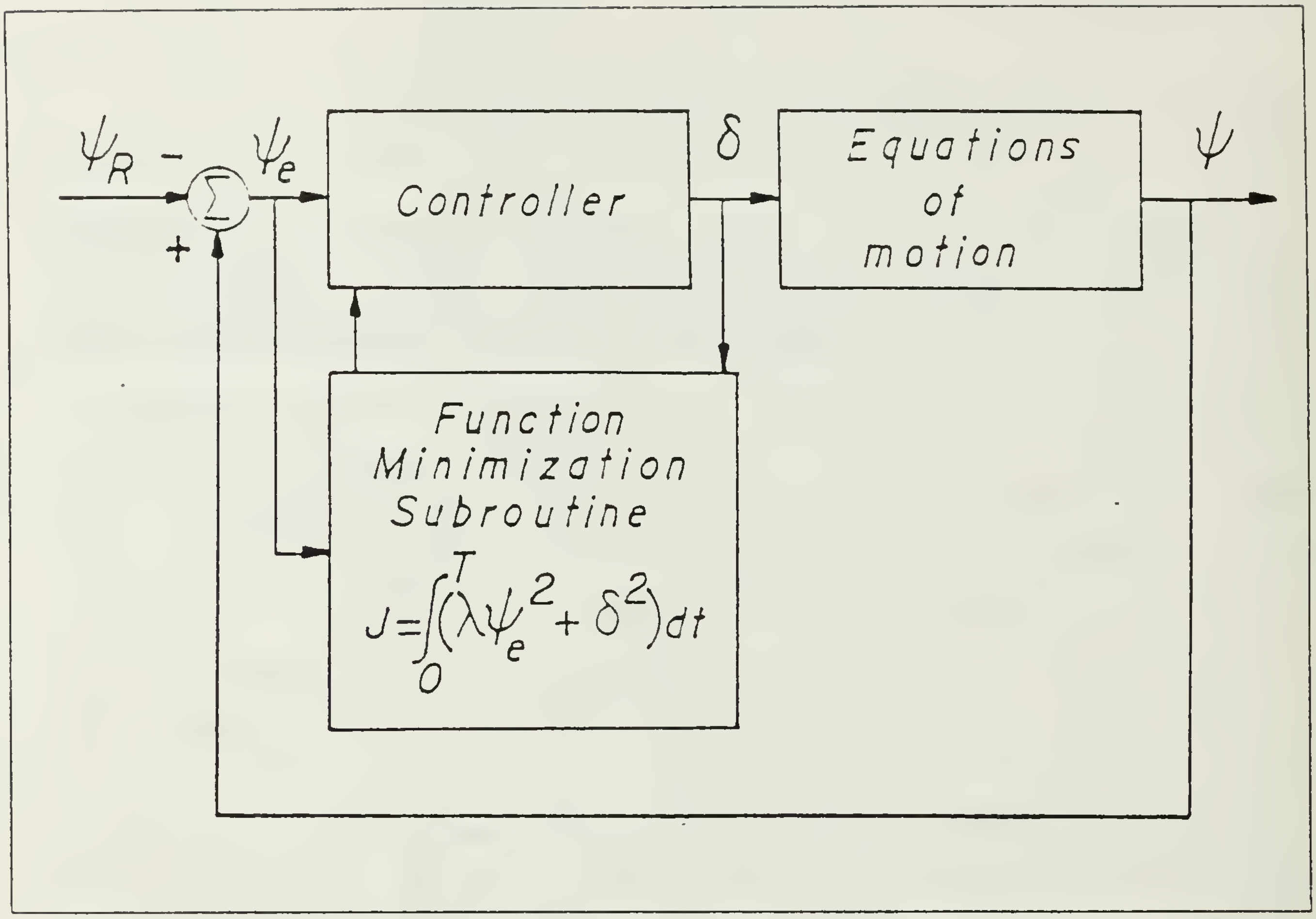

Figure 2.1 Controller Optimization Scheme

$$\frac{\psi}{\delta}=\frac{K}{s(Ts+1)}$$

Second order

$$\frac{\psi}{\delta}=\frac{K(T_Z s+1)}{s(T_{P1}s+1)(T_{P2}s+1)}$$

Third order

Figure 2.2 Nomoto Transfer Functions

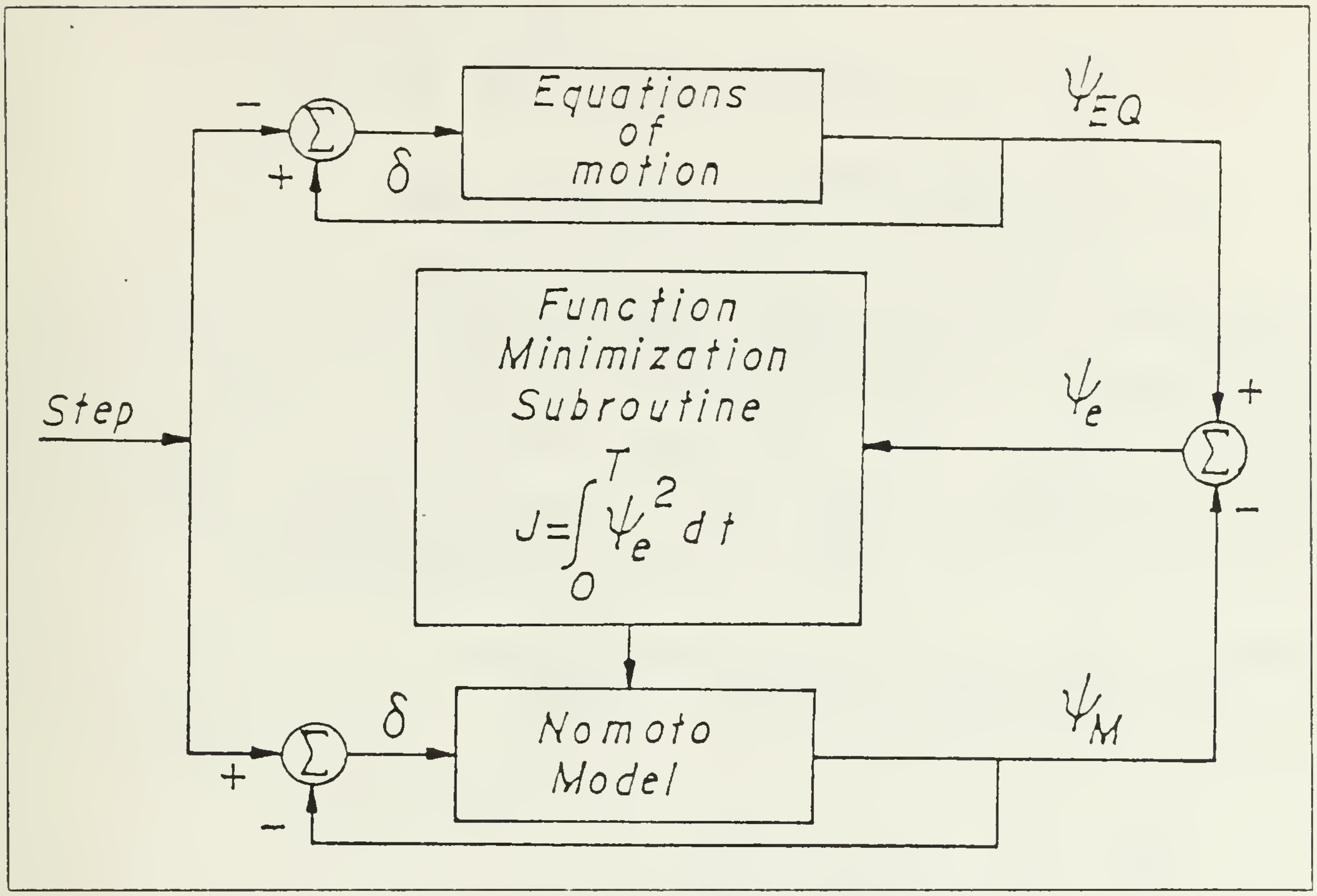

Figure 2.3 Nomoto Model Determination Scheme

representation was adopted because the system is dynamic and use of the Nomoto model representation implies additional computer use. On the other hand, frequency domain studies were carried out using the Nomoto representation since this representation is easier handled.

III. AN ADEQUATE PERFORMANCE CRITERION

A. CRITERION BASED ON TRUE ADDED RESISTANCE

The performance criterion which characterizes propulsion losses due to steering may be shown to be that derived from excess power consumption per unit distance caused due to steering [Ref. 1, 6]. The added resistance due to steering can be related to the surge or thrust equation where the total instantaneous surge relevant to steering is

$$\Delta X = [m + (\rho/2)LAX'_{vr}]vr + 1/2[(\rho/2)AX'_{vv}]v^2 + 1/2[(\rho/2)AX'_{\delta\delta}U^2]\delta^2 \qquad (3.1)$$

where m = mass of ship

ρ = density of sea water

L = ship's length between perpendiculars

$A = L^2$

U = ship's water speed

v = sway velocity

r = yaw rate of ship

δ = rudder angle

X'_{vr} = force coefficient due to yaw/sway (positive)

$X'_{\delta\delta}$ = force coefficient due to rudder angle (negative)

X'_{vv} = force coefficient due to sway

Since the sway velocity of the ship is small we can neglect the term which includes the square of the sway velocity in the previous equation. From this the mean surge relevant to steering may be written as

$$\overline{\Delta X}=[m+(\rho/2)LAX'_{vr}](u_a r_a/2)\cos(\varphi_v-\varphi_r) + [(\rho/2)AX'_{\delta\delta}U^2](\delta^2/2) \qquad (3.2)$$

Where u_a = amplitude of sway velocity
r_a = amplitude of yaw rate
δ_a = amplitude of rudder angle
$\varphi_v-\varphi_r$ = phase difference between sway and yaw rate

A performance criterion for added resistance due to steering may be formulated as

$$J=\lim_{T\to\infty}(1/2T)\int_0^T(-a\,vr+\gamma U^2\delta^2)dt \qquad (3.3)$$

where a and γ are constants

Accurate knowledge of the nonlinear coefficients X'_{vr} and $X'_{\delta\delta}$ is required for the accuracy of such a criterion. In addition the criterion itself suffers from the disadvantage that sway velocity measurements are not available. Normalizing the last equation the performance criterion will be

$$J_{norm}=\lim_{T\to\infty}(1/2T)\int_0^T(-\lambda''vr+\delta^2)dt \qquad (3.4)$$

where $\lambda''=\{2[m+(\rho/2)LA]X'_{vr}\}/[(\rho/2)X'_{\delta\delta}U^2]$

Table I indicates the values of λ'' for the operating range of speed of the ship studied.

TABLE I

Weighting factor λ''

Ship's speed (knots)	λ''
16	21.5350
23	10.4215
32	5.3900

B. CRITERION BASED ON APPROXIMATE ADDED RESISTANCE

Empirical criteria based on an approximation to added resistance may also be derived. A semiempirical criterion for measuring the relative performance was developed [Ref. 7], based on the assumption of small amplitude oscillations around the steady-state pivot point of the ship during yawing at the ship/steering system natural frequency. This may be extended and an alternative criterion for added resistance will be

$$J = \lim_{T \to \infty} (1/2T) \int_0^T (\lambda \psi_e^2 + \delta^2) dt \qquad (3.5)$$

where

$\lambda = \lambda' \omega = [2m(1+X'_{vr})(\overline{OP}/L)\omega^2]/[(\rho/2)LX'_{\delta\delta}U^2]$

$X'_{vr} = [(\rho/2)LAX'_{vr}]/m$

$\overline{OP}$ = distance from center of gravity to pivot center

ω = natural frequency (closed loop ship steering control)

ψ_e = ship's perturbation yaw angle

The values of λ' as a function of ship's speed are given by Table II.

A closed loop system natural frequency ω of around 0.05 rads per sec has the potential to attenuate the effects of

TABLE II

Weighting factor λ'

Ship's speed (knots)	λ'
16	6,720
23	3,251
32	1,680

seaway disturbance in the range of encounter angles where added resistance due to steering is important [Ref. 6]. The weighting factor for the operating range of the ship is shown in Table III.

TABLE III

Weighting factor λ

Ship's speed (knots)	λ
16	16.796
23	8.128
32	4.2

Equation 3.5 is used as a performance criterion for this study. It is an approximation but it is convenient for onboard use since ship's perturbation yaw angle ψ and rudder angle δ are measurable.

C. WEIGHTING FACTOR STUDY

The weighting factor λ given by Table III used in equation 3.5, plays an important role in terms of the optimal controller parameters determination. Some investigation is necessary in order to verify the accuracy of the results, since the values of λ of Table III are determined based on the assumption that the closed loop system's natural frequency is around 0.05 rads per sec [Ref. 1]. Frequency domain techniques were used for this purpose. Using the Nomoto third order model representation of the ship and available controller parameters from Chapter 4 for sea state

4, encounter frequency 1.5 rads per sec, encounter angle 150° and ship's speed 23 knots we found that the closed loop bandwidth of the system is 0.04 rads per sec, as indicated in Figure 3.1, which is not close enough to 0.05 rads per sec.

For the same sea conditions and ship speed, with the assumption that the closed loop natural frequency of the system is not 0.05 rads per sec but 0.04 rads per sec, a new value $\lambda=5.734$ was obtained and the frequency domain techniques result in a new bandwidth 0.035 rads per sec as is indicated in Figure 3.2.

Clearly, the values of λ given by Table III and used in this study are not the best. Unfortunately, since the full hydrodynamic coefficients of the SL-7 containership are not known we can't develop the surge equation and thus it is still impossible to determine accurate values for the weighting factor λ.

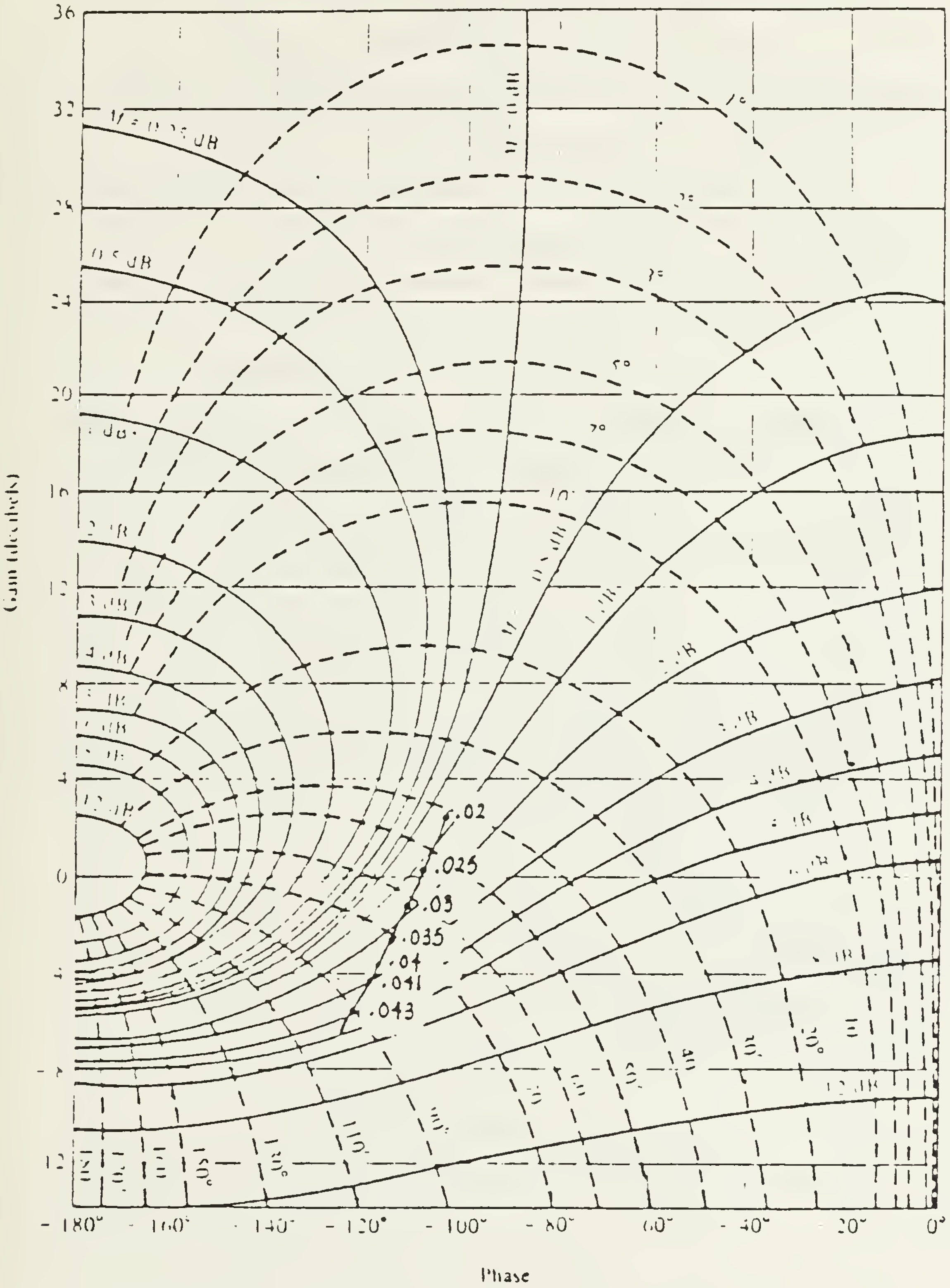

Figure 3.1 Closed Loop Bandwidth for λ=8.128

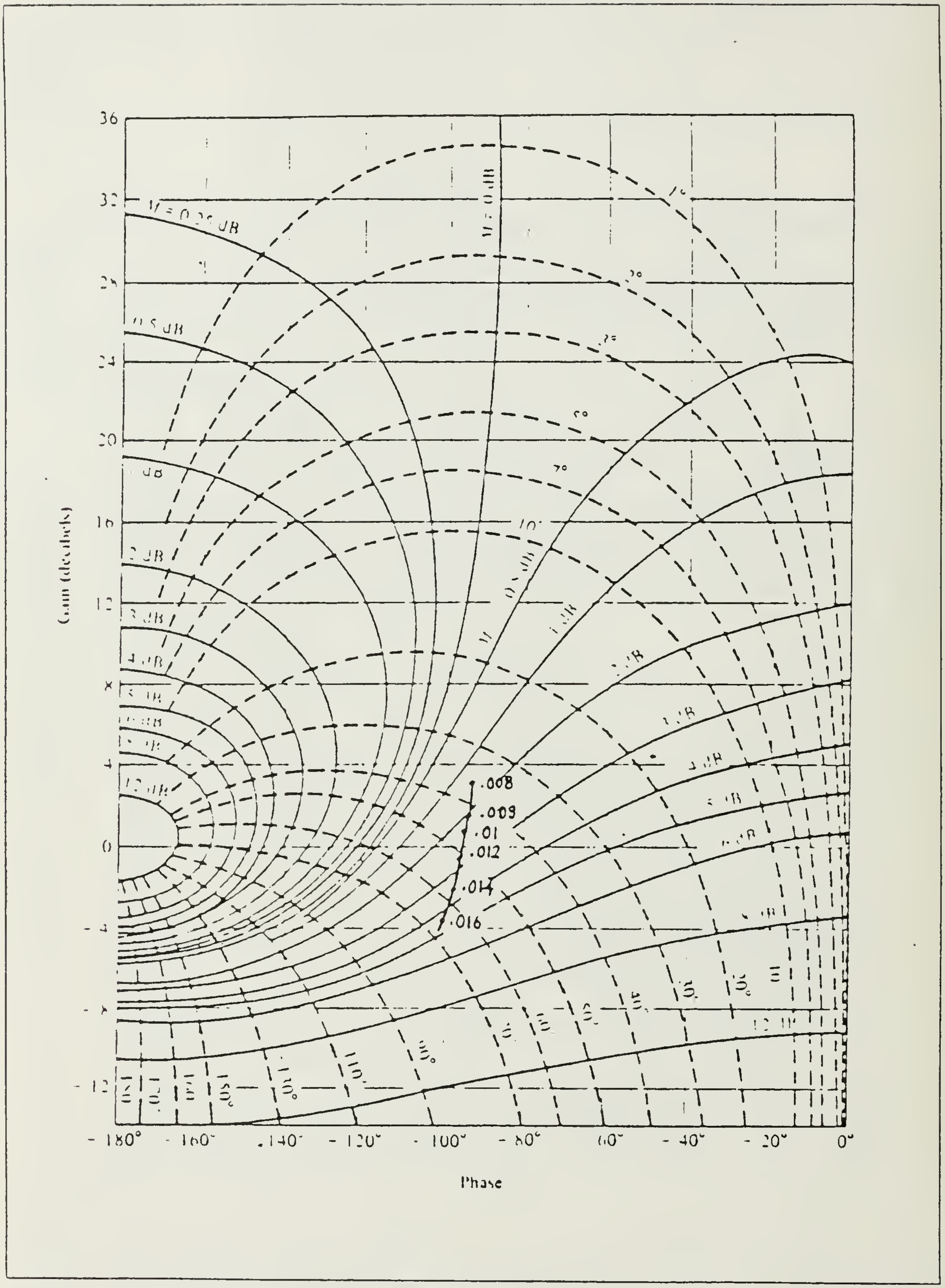

Figure 3.2 Closed Loop Bandwidth for λ=5.734

IV. REGULAR SEAS - CONTROLLER DESIGN

We have already defined a suitable and sufficiently accurate ship computer model and the system's performance criterion, as well. The remaining task is to determine a representation of the external disturbances imparted to the ship by the sea, before the system's performance in a seaway can be evaluated. A correct model of the seaway itself is essential to representative modeling of forces and moments exerted on the ship by it.

At this point we will use the regular sea model as sea representation. The properties of regular seas are well defined. The wave crests are assumed to be straight, infinitely long, parallel and equally spaced with constant wave height. The waves progress in a direction perpendicular to the crest line at a uniform velocity. However the sea is never regular. It is a random phenomenon where waves are continually changing in height, length and breadth [Ref. 8].

The forces exerted by the regular sea have the form

$$F=\omega_a R_i \cos(\omega_e t+\vartheta_i) \tag{4.1}$$

where ω_a = significant wave height
R_i = exciting force
ω_e = encounter frequency
ϑ_i = phase angle

The correspondence between sea state and wave height is indicated in Table IV [Ref. 9].

The exciting forces R_i for different encounter frequencies and encounter angles were obtained from the sea state generator program [Ref. 10].

TABLE IV

Sea state vs Wave height

Sea state (Beaufort scale)	Range for wave height (Feet)
0	0.0
1	0.32
2	0.65-0.98
3	1.96-3.28
4	3.28-4.92
5	6.56-8.20
6	9.84-13.1
7	13.1-18.2
8	18.2-24.6
9	23.0-32.9

Appendix B indicates the regular seastate formulation in the FORTRAN program used for obtaining the controller parameters.

The controller used in the entire study has one pole-one zero and the form is indicated in Figure 4.1. This controller seems to have the best performance in calm waters and in seaway [Ref. 5].

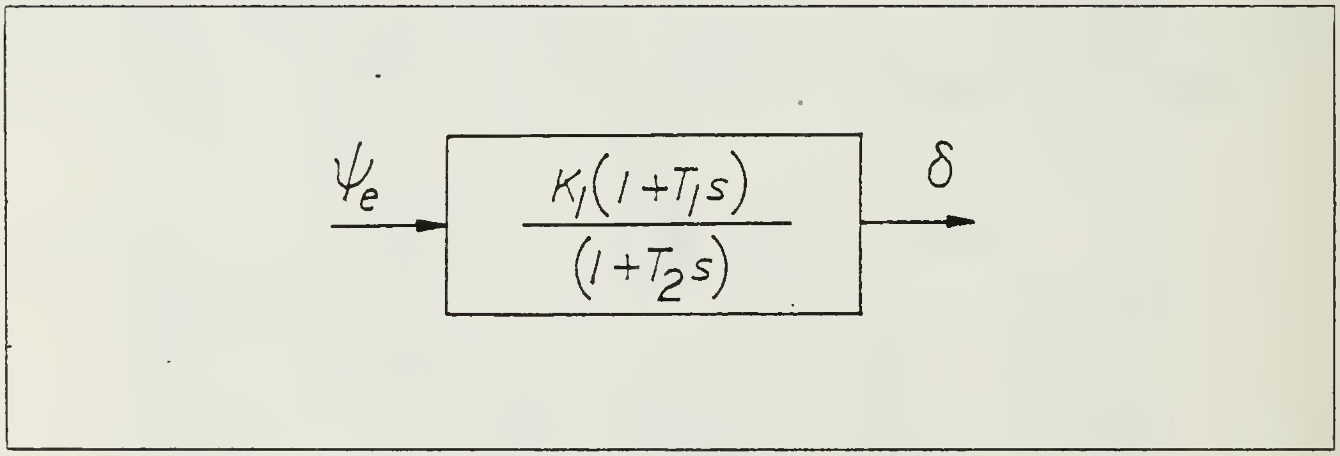

Figure 4.1 Controller Used in this Study

The optimized controller parameters and the cost J for 23 knots speed, sea states 4-6-7-9, different encounter angles and various encounter frequencies are indicated in Tables V,VI,VII and VIII.

Studying the Tables V through VIII we can draw the following conclusions:

- For a particular encounter angle and encounter frequency the higher the sea state the higher the cost.
- For the same sea state the cost becomes smaller for higher encounter frequencies.
- For encounter frequency 0.2 rads per sec the maximum cost occurs at 60° encounter angle for all tested sea states.
- For 0.6 and 0.75 rads per sec encounter frequency the maximum cost occurs at 120° encounter angle for all tested sea states.
- For 1.5 rads per sec encounter frequency the maximum cost occurs at 90° encounter angle for all tested sea states.
- For 0.4 rads per sec encounter frequency the maximum cost occurs at 90° encounter angle for sea states 4,6 and 7 while at sea state 9 the maximum cost occurs at 60° encounter angle.

Appendix C provides the computer program necessary to achieve the system's response. Some typical responses are indicated in Figures 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 4.8, 4.9. It is obvious that as the sea state goes to heavier seas the rudder and yaw perturbations become larger.

An attempt to determine how accurate the controller parameters must be for a particular situation, leads to the conclusion that high accuracy isn't required. Keeping two parameters fixed each time and vary the third we can see (Figures 4.10, 4.11, 4.12, 4.13, 4.14) that the cost doesn't change appreciably in the vicinity of the actual value.

Figures 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 4.8, 4.9 indicate that the yaw and rudder excursions are less than 1°. This just seems strange, though it may be because of the optimization of the filter. We tried to investigate that by

using the optimal filter for sea state 9, encounter frequency 1.5 rads per sec, encounter angle 120° and run it in sea state 4, keeping the same encounter frequency and angle. The yaw and rudder excursions, even if they became larger, remained less than 1°. The parameters of those two filters are close and the reason might be the flatness of the cost surface. Second attempt led to more interesting results. Using the same filter and run it in sea state 4, encounter frequency 0.4 rads per sec and encounter angle 060°, the system becomes unstable (Figures 4.15, 4.16).

TABLE V

Optimal Controller Parameters for Regular Sea
Sea State 4

Encounter Frequency 0.2 rads per sec

encounter angle(degrees)	K1	T1	T2	J
0	0.5221067	66.3312231	12.8332741	0.609E-33
30	1.0488701	61.9309387	15.9266357	2.4819
60	1.2036362	54.5533295	16.0245972	3.612223
90	1.3178062	49.7426453	14.8329315	2.703524
120	1.3984699	46.9797058	13.9525757	1.355578
150	1.4502153	45.4263306	13.3351599	0.3567196
180	0.7195223	25.2119598	14.1219782	0.345E-28

Encounter Frequency 0.4 rads per sec

encounter angle(degrees)	K1	T1	T2	J
0	0.5221067	66.3312231	12.8332741	0.517E-35
30	0.7234516	74.7846533	47.9879893	0.54673
60	0.8730211	92.8420868	50.0454407	1.194746
90	2.8910360	28.9679871	10.0176315	2.536161
120	2.6232796	27.9702454	8.8327761	0.2349457
150	2.6408129	27.7937927	8.6838455	0.0545772
180	0.7195223	25.2119598	14.1219782	0.536E-32

Encounter Frequency 0.6 rads per sec

encounter angle(degrees)	K1	T1	T2	J
0	0.5221067	66.3312231	12.8332741	0.453E-31
30	2.0506487	1.2107763	5.5998001	0.0028366
60	1.0504951	0.2329917	19.0010876	0.0031525
90	2.1496201	1.2607498	5.3318434	0.0790777
120	2.1221027	0.9715905	6.9064713	0.0796856
150	1.9617786	0.8480816	8.3953667	0.0341976
180	0.7195223	25.2119598	14.1219782	0.147E-39

Encounter Frequency 0.75 rads per sec

encounter angle(degrees)	K1	T1	T2	J
0	0.5221067	66.3312231	12.8332741	0.711E-35
30	2.4342451	0.8039263	7.4397717	0.0017128
60	2.3829517	0.8094406	8.6272535	0.0042339
90	2.0794163	0.4690621	16.9594727	0.0442135
120	1.9938784	0.2545378	22.4892426	0.1164415
150	1.9387684	0.2628353	23.8461609	0.0379958
180	0.7195223	25.2119598	14.1219782	0.312E-23

Encounter Frequency 1.5 rads per sec

encounter angle(degrees)	K1	T1	T2	J
0	0.5221067	66.3312231	12.8332741	0.143E-35
30	1.8784037	0.6553955	5.4344263	0.0000847
60	2.4894753	0.5992758	5.1160698	0.0014724
90	2.5899792	0.6663168	3.1813316	0.0241299
120	1.8784037	0.5395500	10.4344263	0.0028635
150	2.4478331	0.5559916	5.9208412	0.0015984
180	0.7195223	25.2119598	14.1219782	0.451E-28

TABLE VI

Optimal Controller Parameters for Regular Sea
Sea State 6

Encounter Frequency 0.2 rads per sec

encounter angle(degrees)	K1	T1	T2	J
0	0.5221067	66.3312231	12.8332741	0.322E-33
30	1.0966187	62.3766327	19.3941193	8.622314
60	1.2665367	55.1072540	19.2263336	11.84099
90	1.3603411	49.3086395	16.7315979	9.270265
120	1.4170542	46.4313202	14.7203903	5.004774
150	1.4533644	45.2830963	13.6198730	1.396385
180	0.7195223	25.2119598	14.1219782	0.678E-28

Encounter Frequency 0.4 rads per sec

encounter angle(degrees)	K1	T1	T2	J
0	0.5221067	66.3312231	12.8332741	0.122E-31
30	0.7536127	12.4472111	4.8151121	2.3798
60	1.1621914	1.7206783	5.6173820	4.143427
90	2.8681517	28.5688019	11.3736725	7.7779746
120	2.6123600	28.0108032	9.1387405	0.8634676
150	2.6361399	27.8540497	8.7665482	0.2140626
180	0.7195223	25.2119598	14.1219782	0.345E-25

Encounter Frequency 0.6 rads per sec

encounter angle(degrees)	K1	T1	T2	J
0	0.5221067	66.3312231	12.8332741	0.806E-35
30	2.0449467	1.2405663	5.5909785	0.0113364
60	1.0594482	0.1432046	18.5202637	0.0126108
90	2.1537333	1.1794500	5.9987049	0.2766824
120	2.1456242	0.9514294	7.3327799	0.3125796
150	1.9752455	0.8255181	8.5351868	0.1364259
180	0.7195223	25.2119598	14.1219782	0.112E-23

Encounter Frequency 0.75 rads per sec

encounter angle(degrees)	K1	T1	T2	J
0	0.5221067	66.3312231	12.8332741	0.753E-32
30	2.4413719	0.7599964	7.3472633	0.0068484
60	2.4142313	0.7818718	8.5500679	0.0169234
90	2.0592680	0.3840635	19.2782745	0.1523162
120	2.0695038	0.2843146	22.5692444	0.4640285
150	1.9513931	1.2351496	23.5140228	0.1518951
180	0.7195223	25.2119598	14.1219782	0.691E-28

Encounter Frequency 1.5 rads per sec

encounter angle(degrees)	K1	T1	T2	J
0	0.5221067	66.3312231	12.8332741	0.321E-33
30	1.7606564	0.4668925	12.3475494	0.0003390
60	2.5002985	0.5747030	5.3262844	0.0058868
90	2.6015043	0.6543975	3.2408133	0.0946725
120	2.1809998	0.4698086	10.9160814	0.0114672
150	2.4302263	0.5666089	6.0247307	0.0063947
180	0.7195223	25.2119598	14.1219782	0.344E-23

TABLE VII

Optimal Controller Parameters for Regular Sea
Sea State 7

Encounter Frequency 0.2 rads per sec

encounter angle(degrees)	K1	T1	T2	J
0	0.5221067	66.3312231	12.8332741	0.911E-35
30	1.1839037	68.3722687	27.3912964	19.62723
60	1.3688898	65.5752258	30.9693604	24.53816
90	1.4492817	53.9667511	23.6652069	20.31325
120	1.4652090	46.2668457	17.1322327	12.58828
150	1.4653692	44.8378906	14.1106033	4.036665
180	0.7195223	25.2119598	14.1219782	0.912E-32

Encounter Frequency 0.4 rads per sec

encounter angle(degrees)	K1	T1	T2	J
0	0.5221067	66.3312231	12.8332741	0.341E-30
30	0.6452138	38.7243542	11.6571761	0.0524352
60	2.2381306	1.0741718	9.7088852	10.22498
90	2.7780743	30.6558838	16.9282227	11.95129
120	2.5894566	28.1353302	10.0156784	2.098495
150	2.6306906	27.8760681	8.9550962	0.6211755
180	0.7195223	25.2119598	14.1219782	0.176E-35

Encounter Frequency 0.6 rads per sec

encounter angle(degrees)	K1	T1	T2	J
0	0.5221067	66.3312231	12.8332741	0.157E-31
30	2.0501146	1.2125063	5.5930214	0.0346353
60	1.0624285	0.1251755	18.0873718	0.0386276
90	2.1488247	0.9770966	8.1855469	0.6328694
120	2.1970577	0.8763103	8.4206886	0.9178923
150	2.0124264	0.8064904	8.9983368	0.4150548
180	0.7195223	25.2119598	14.1219782	0.441E-28

Encounter Frequency 0.75 rads per sec

encounter angle(degrees)	K1	T1	T2	J
0	0.5221067	66.3312231	12.8332741	0.238E-28
30	2.4456072	0.8701959	7.6628313	0.0209509
60	2.4188919	0.8008499	8.6116581	0.0517269
90	1.9072247	0.1301596	28.8665771	0.4958954
120	2.2209492	0.3453745	22.8497772	1.398130
150	2.0318069	0.2577103	23.6702576	0.4641950
180	0.7195223	25.2119598	14.1219782	0.542E-21

Encounter Frequency 1.5 rads per sec

encounter angle(degrees)	K1	T1	T2	J
0	0.5221067	66.3312231	12.8332741	0.712E-32
30	2.0834208	0.4371362	15.1762695	0.0010384
60	2.4635468	0.5746776	5.3325920	0.0180051
90	2.6105270	0.6474890	3.4996614	0.2765892
120	2.1780138	0.4588630	11.4343033	0.0352355
150	2.4314880	0.5580992	6.0874767	0.0195939
180	0.7195223	25.2119598	14.1219782	0.413E-26

TABLE VIII

Optimal Controller Parameters for Regular Sea
Sea State 9

Encounter Frequency 0.2 rads per sec

encounter angle(degrees)	K1	T1	T2	J
0	0.5221067	66.3312231	12.8332741	0.493E-31
30	1.2344990	97.2906342	53.3980713	31.88802
60	1.5019569	77.3820190	45.6973572	30.87321
90	1.5020103	77.2400513	45.6112671	30.87321
120	1.5420017	51.2350922	23.8943634	21.75188
150	1.4879055	44.4281464	15.2255249	8.599576
180	0.7195223	25.2119598	14.1219782	0.810E-39

Encounter Frequency 0.4 rads per sec

encounter angle(degrees)	K1	T1	T2	J
0	0.5221067	66.3312231	12.8332741	0.743E-33
30	0.1618259	95.8238471	18.3397064	8.103665
60	2.3103380	0.9894915	12.5459442	20.30595
90	3.3482129	2.6129665	4.7000313	7.494904
120	2.5573978	28.7854462	12.1667938	3.113852
150	2.6185656	27.9137726	9.3553696	1.324692
180	0.7195223	25.2119598	14.1219782	0.534E-33

Encounter Frequency 0.6 rads per sec

encounter angle(degrees)	K1	T1	T2	J
0	0.5221067	66.3312231	12.8332741	0.478E-31
30	2.0493793	1.2093735	5.6404839	0.0820505
60	1.1003008	0.1920759	18.7369995	0.0919840
90	2.0454016	0.5407953	15.4096680	1.031631
120	2.2776527	0.7766371	10.4350891	2.069717
150	2.0829115	0.7725539	9.8721237	0.9771649
180	0.7195223	25.2119598	14.1219782	0.117E-29

Encounter Frequency 0.75 rads per sec

encounter angle(degrees)	K1	T1	T2	J
0	0.5221067	66.3312231	12.8332741	0.872E-35
30	2.4433956	0.8601446	7.7009745	0.0497640
60	2.4255047	0.7809458	8.7044067	0.1226490
90	2.2933350	0.4751374	16.7149658	0.7522082
120	2.3928595	0.4103206	22.9515076	3.146294
150	2.1456175	0.2891768	23.5924225	1.097565
180	0.7195223	25.2119598	14.1219782	0.611E-26

Encounter Frequency 1.5 rads per sec

encounter angle(degrees)	K1	T1	T2	J
0	0.5221067	66.3312231	12.8332741	0.242E-33
30	2.0808840	0.4744592	16.3423157	0.0024732
60	2.4694090	0.5775681	5.4030972	0.0042757
90	2.6412249	0.6233797	3.9802380	0.6127556
120	2.1955976	0.4414446	12.1491365	0.0084519
150	2.4388838	0.5490999	6.1774960	0.0046688
180	0.7195223	25.2119598	14.1219782	0.420E-30

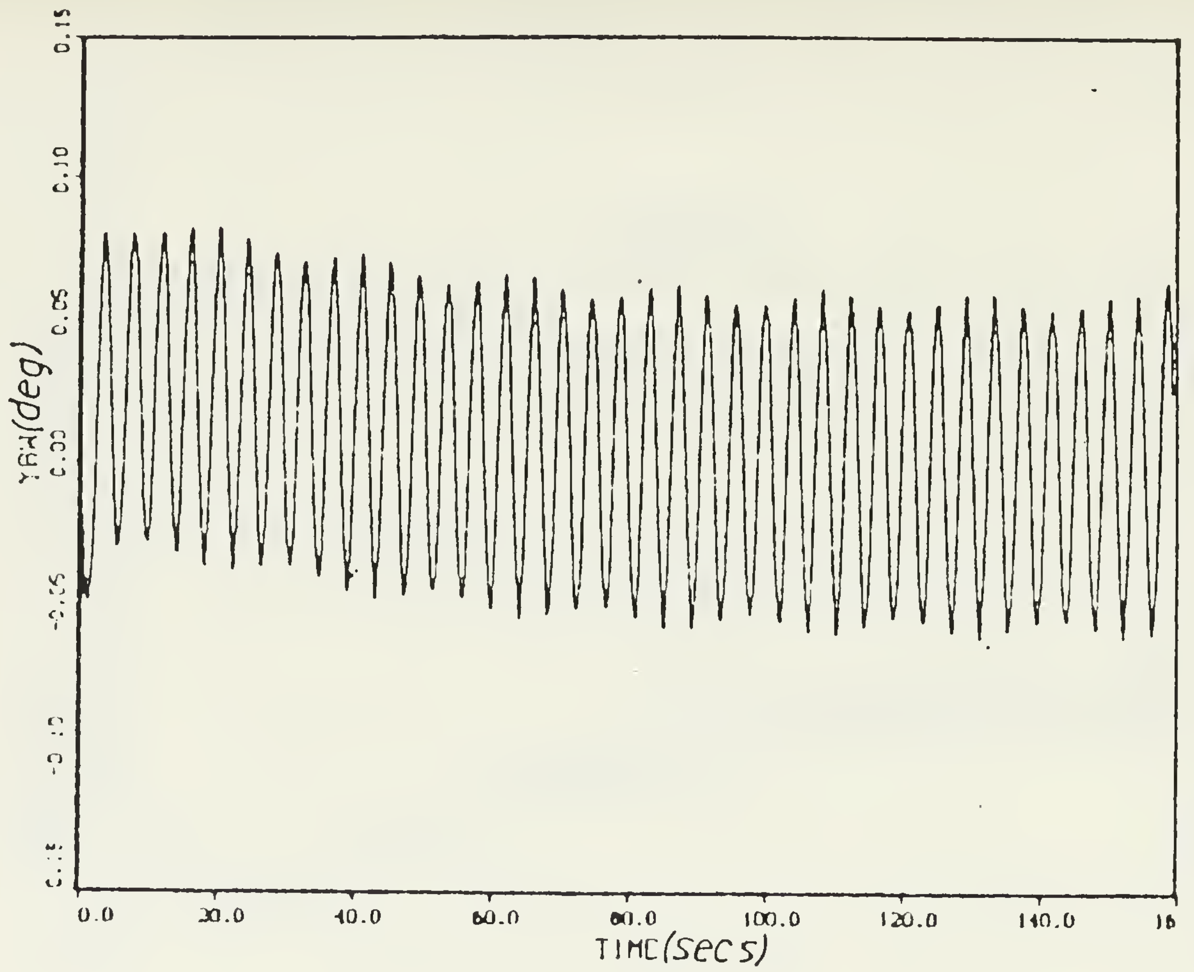

Figure 4.2 Yaw vs Time, Sea State 4.
Encounter Frequency 1.5 rads per sec, Encounter Angle 120°

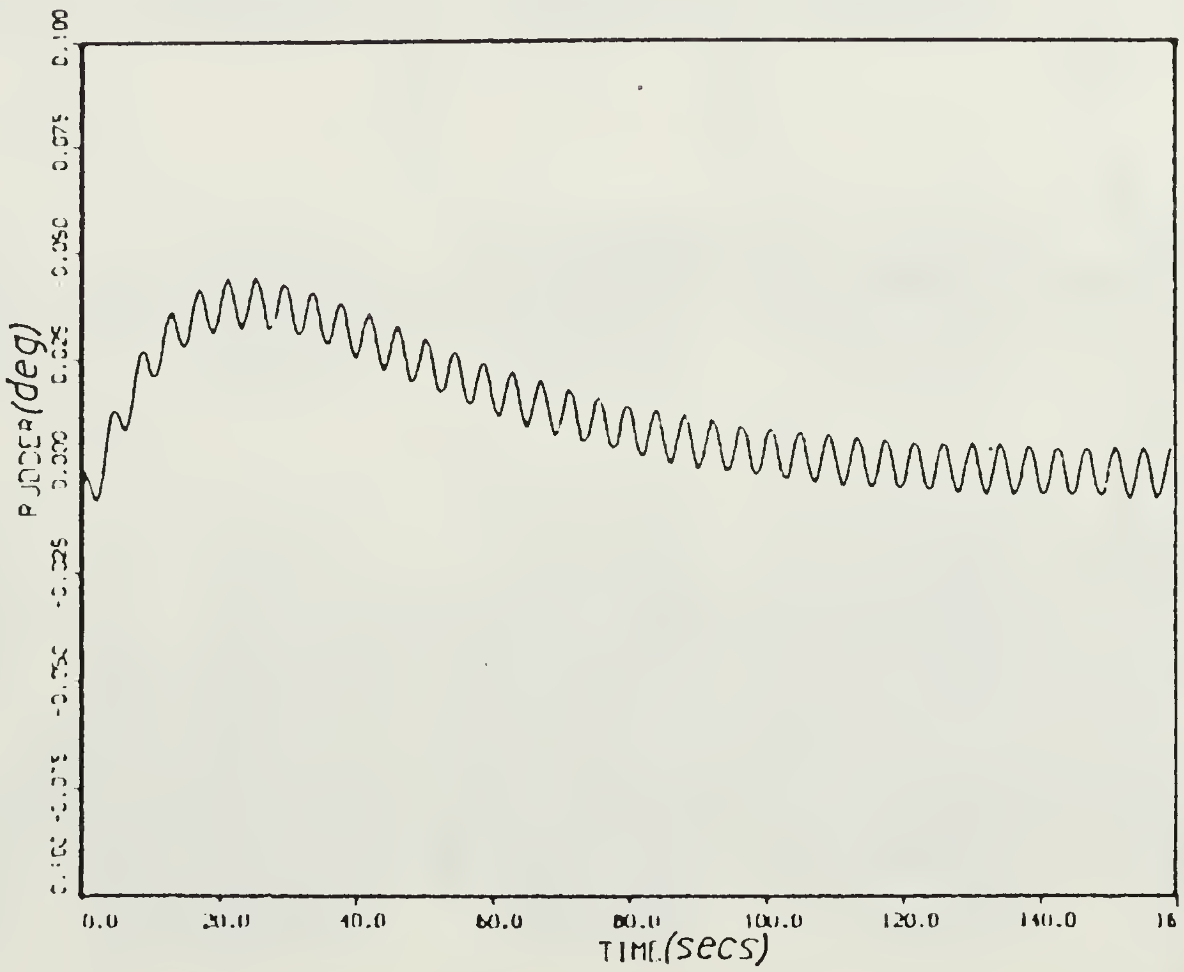

Figure 4.3 Rudder vs Time, Sea State 4.
Encounter Frequency 1.5 rads per sec, Encounter Angle 120°

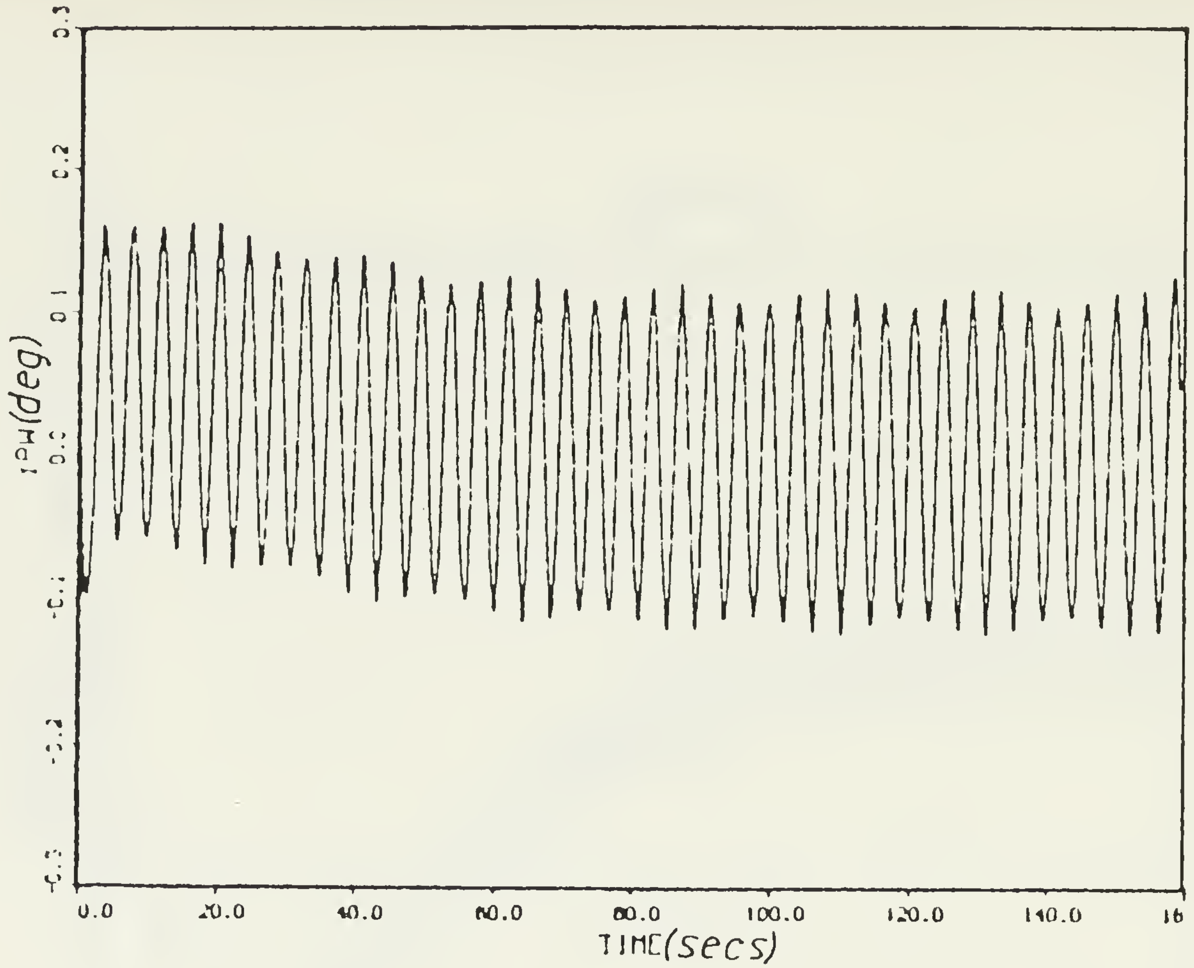

Figure 4.4 Yaw vs Time, Sea State 6.
Encounter Frequency 1.5 rads per sec, Encounter Angle 120°

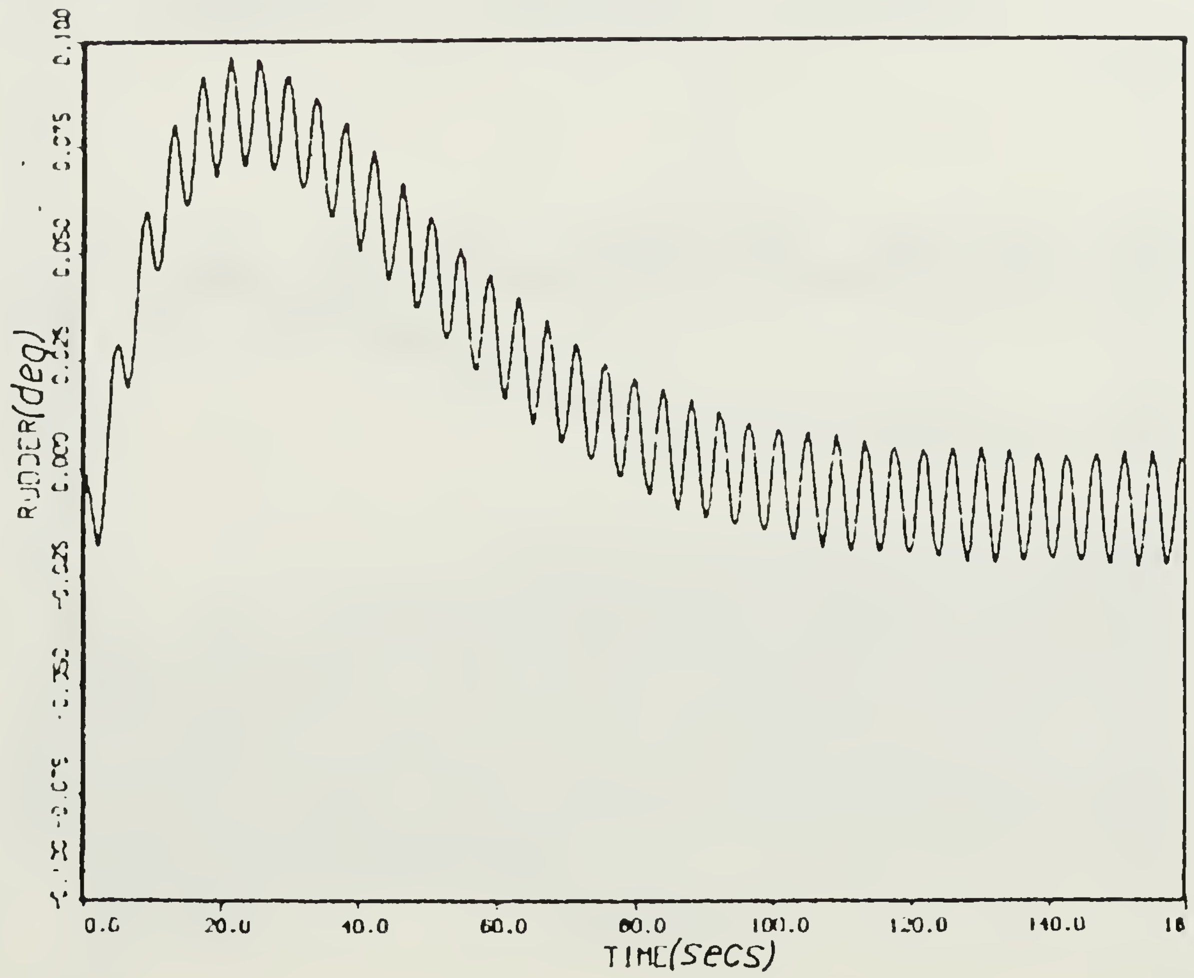

Figure 4.5 Rudder vs Time, Sea State 6.
Encounter Frequency 1.5 rads per sec, Encounter Angle 120°

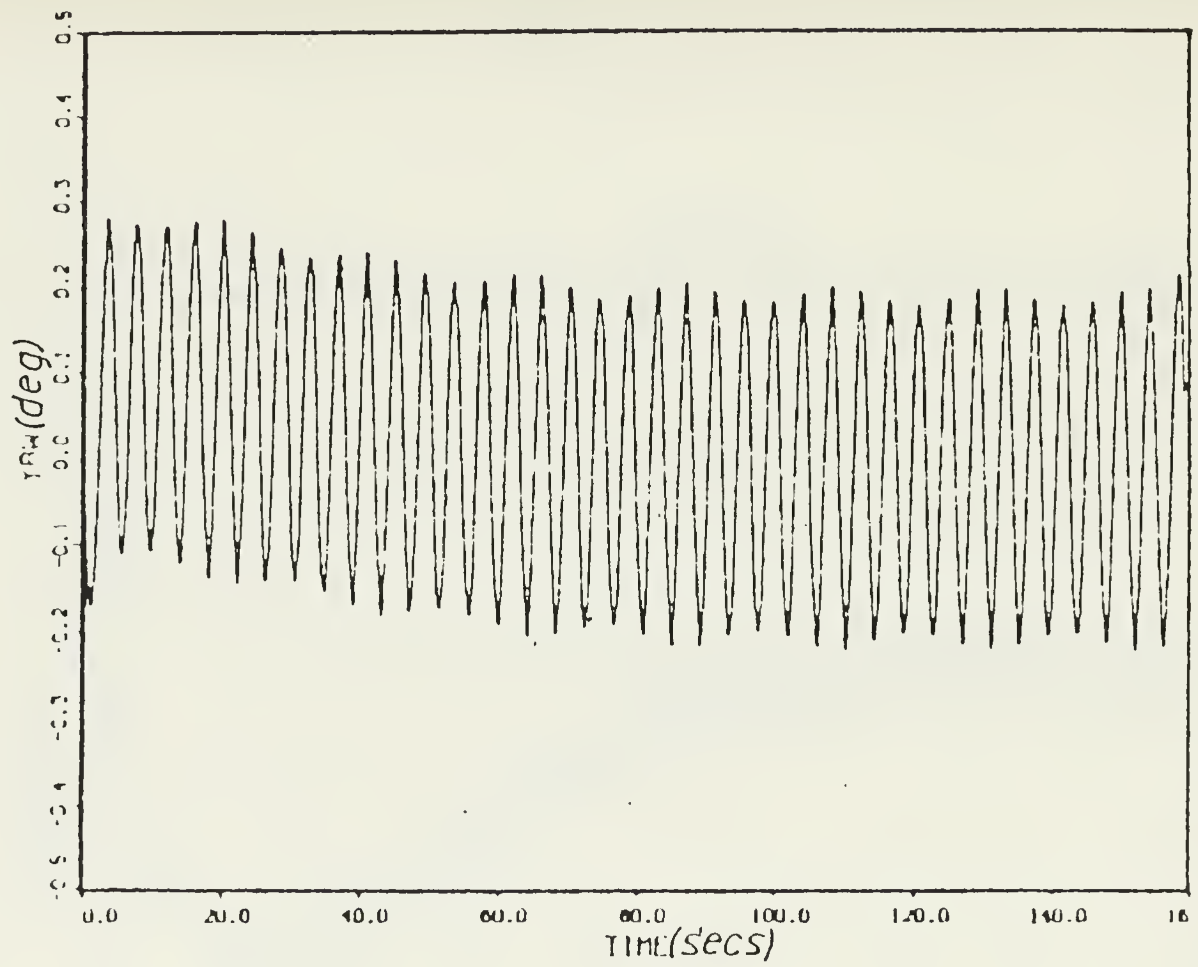

Figure 4.6 Yaw vs Time, Sea State 7.
Encounter Frequency 1.5 rads per sec, Encounter Angle 120°

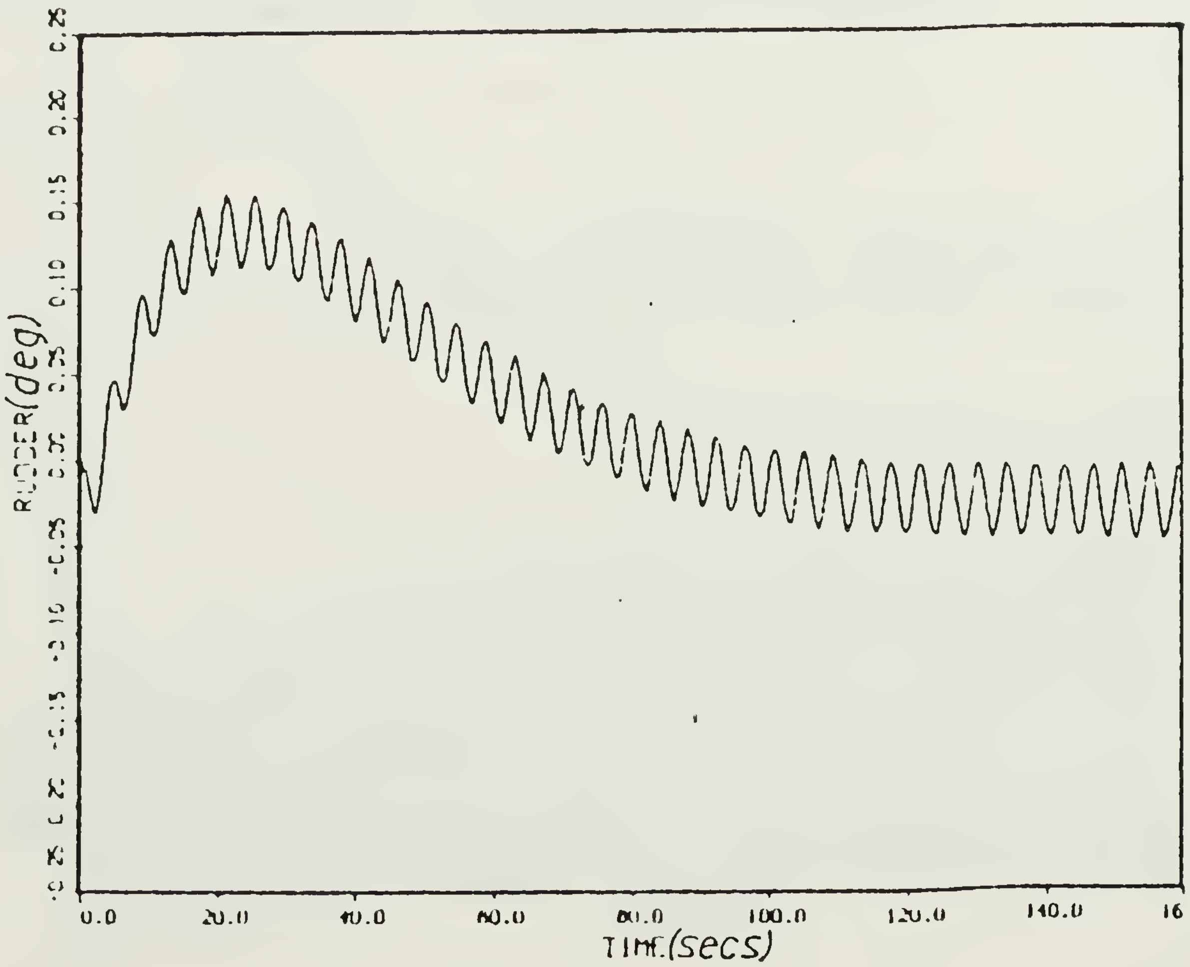

Figure 4.7 Rudder vs Time, Sea State 7.
Encounter Frequency 1.5 rads per sec, Encounter Angle 120°

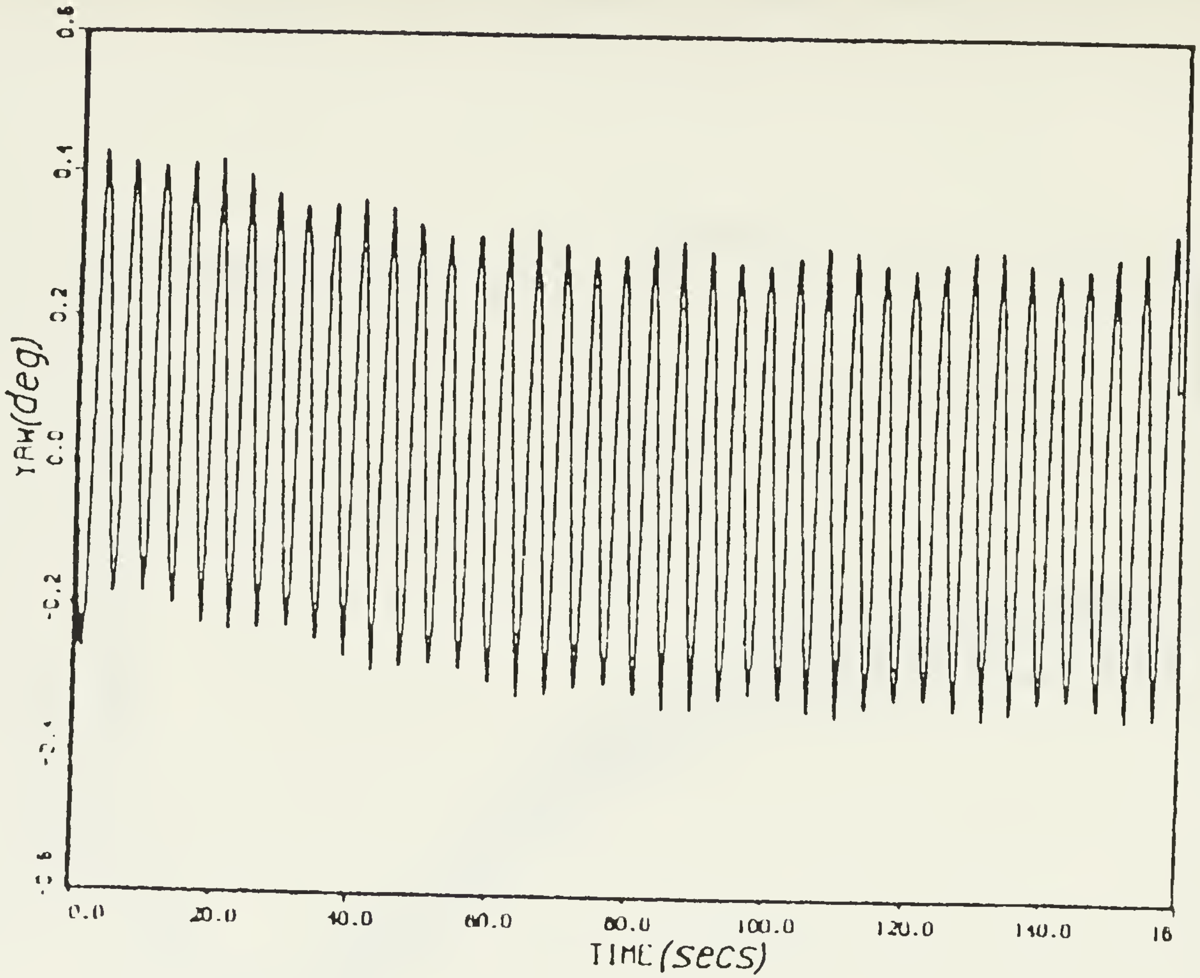

Figure 4.8 Yaw vs Time, Sea State 9.
Encounter Frequency 1.5 rads per sec, Encounter Angle 120°

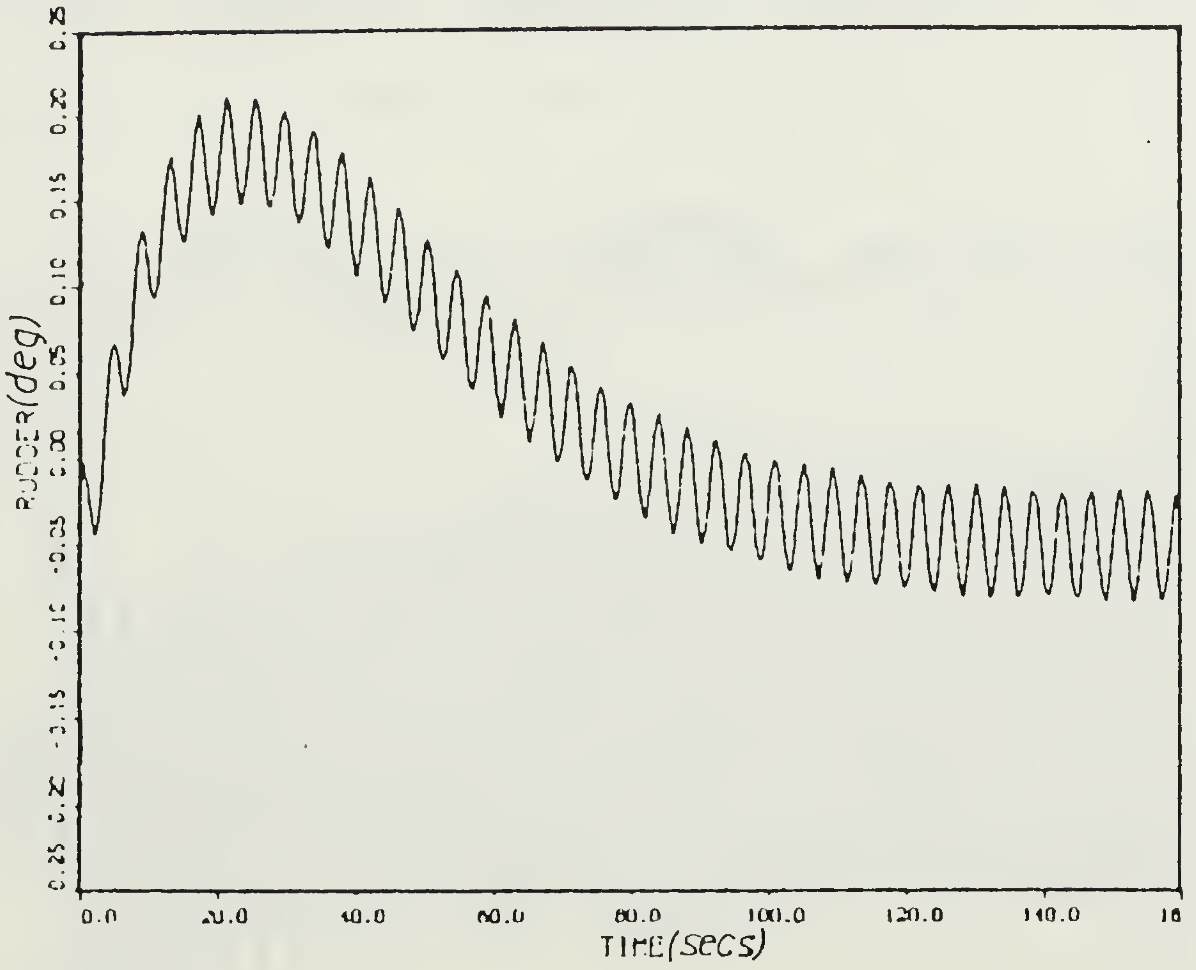

Figure 4.9 Rudder vs Time, Sea State 9.
Encounter Frequency 1.5 rads per sec, Encounter Angle 120°

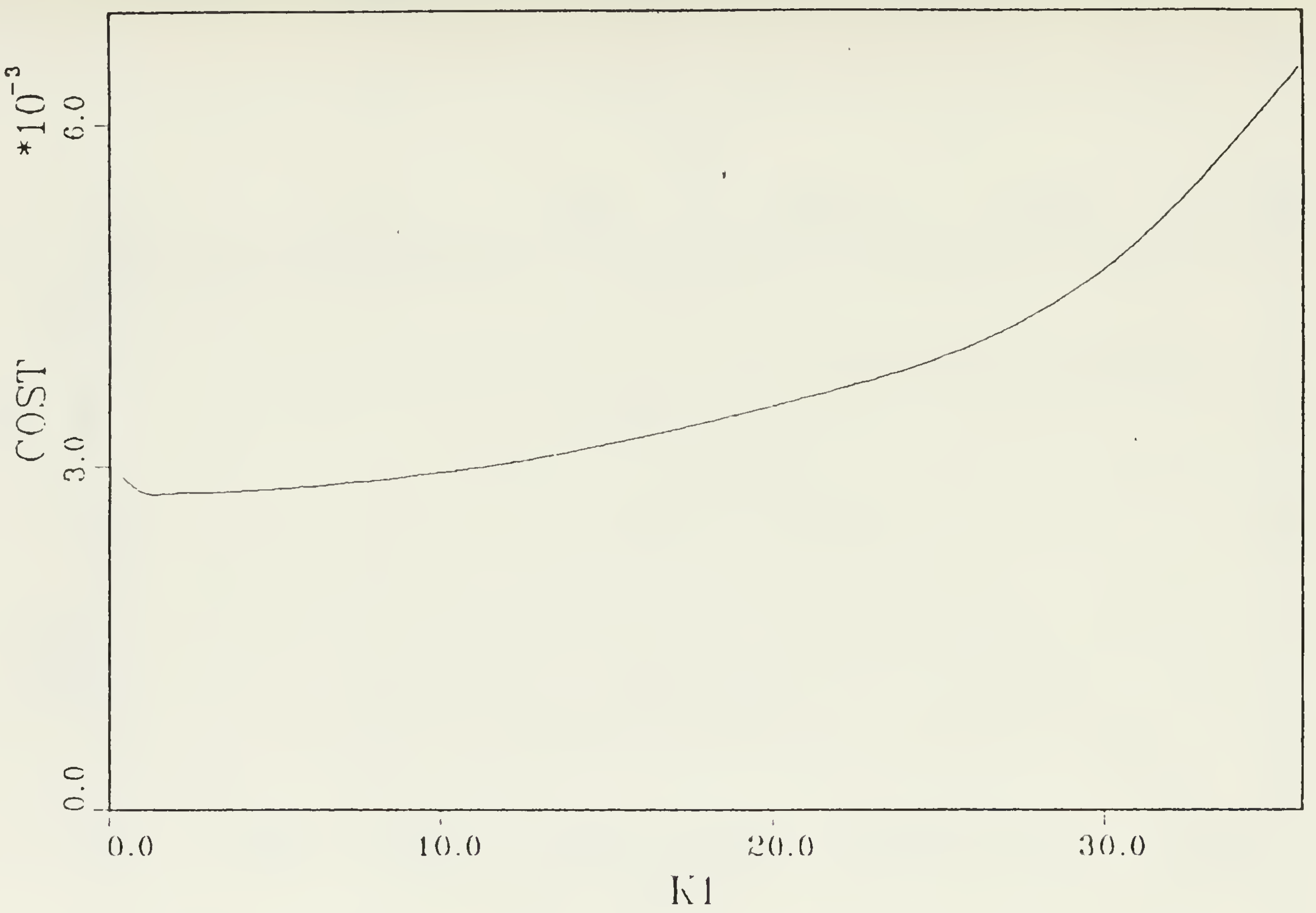

Figure 4.10 Cost vs K1,Sea State 4.
Encounter frequency 1.5 rads per sec, Encounter Angle 120°

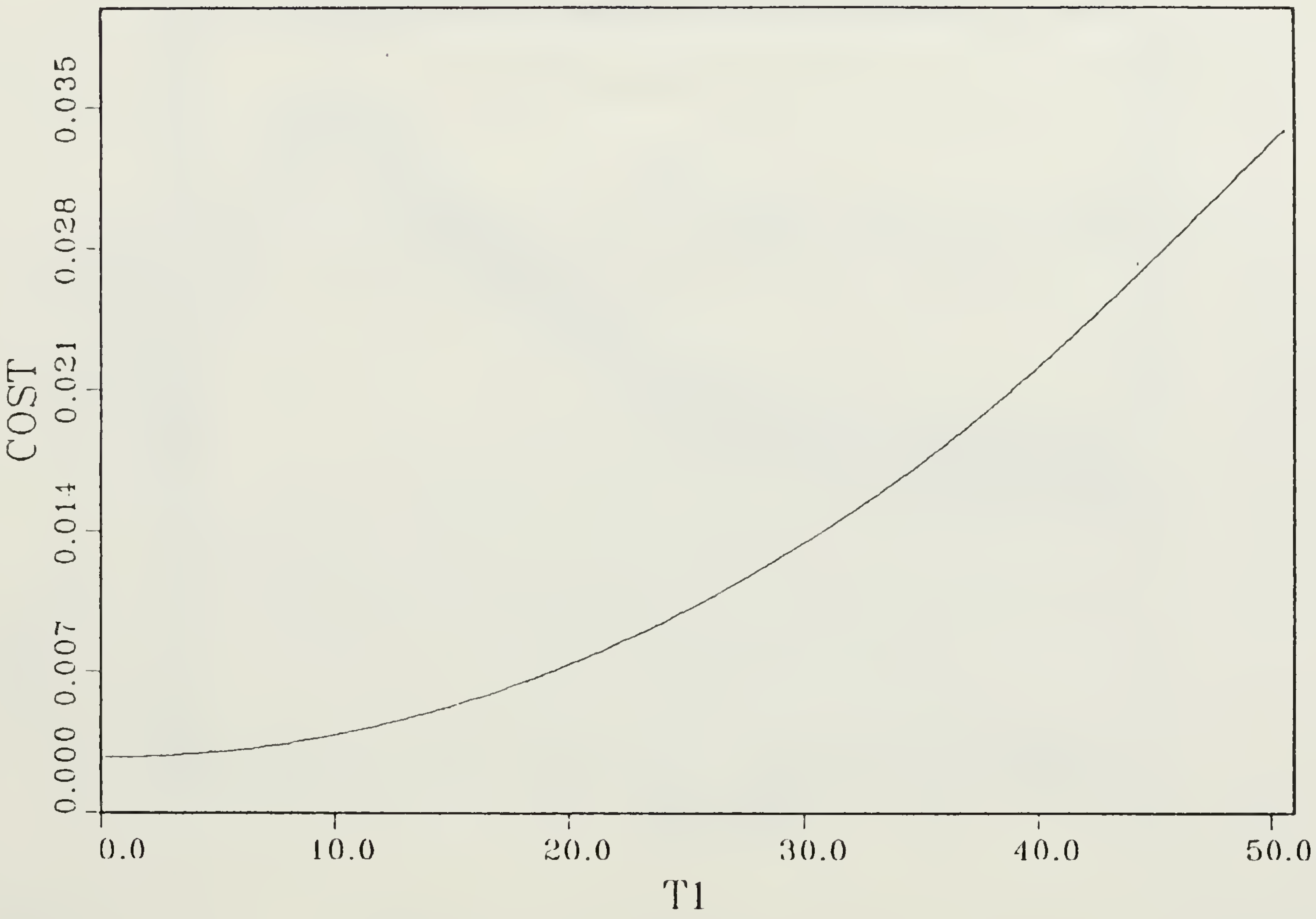

Figure 4.11 Cost vs T1, Sea State 4.
Encounter frequency 1.5 rads per sec, Encounter Angle 120°

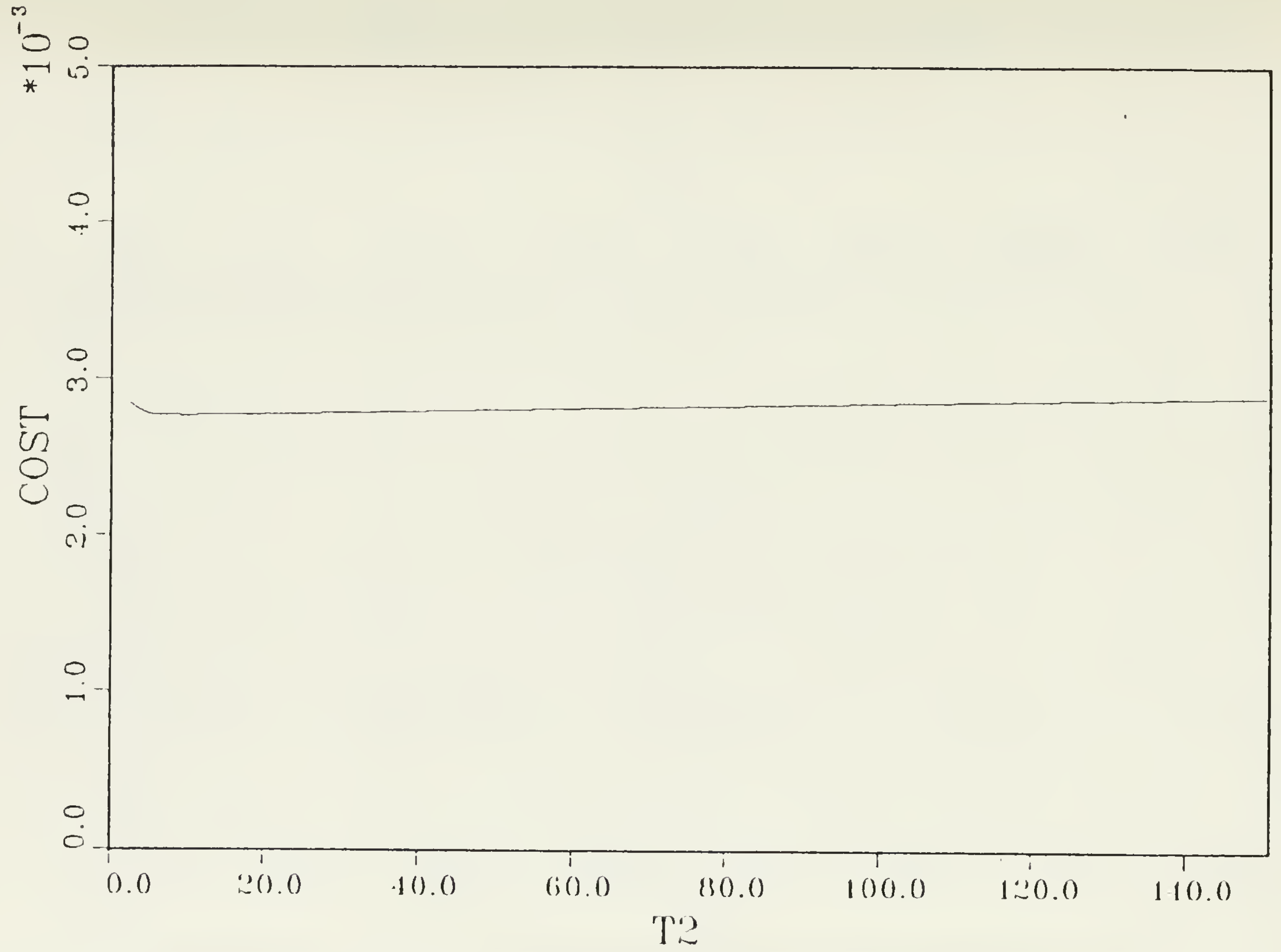

Figure 4.12 Cost vs T2, Sea State 4.
Encounter frequency 1.5 rads per sec, Encounter Angle 120°

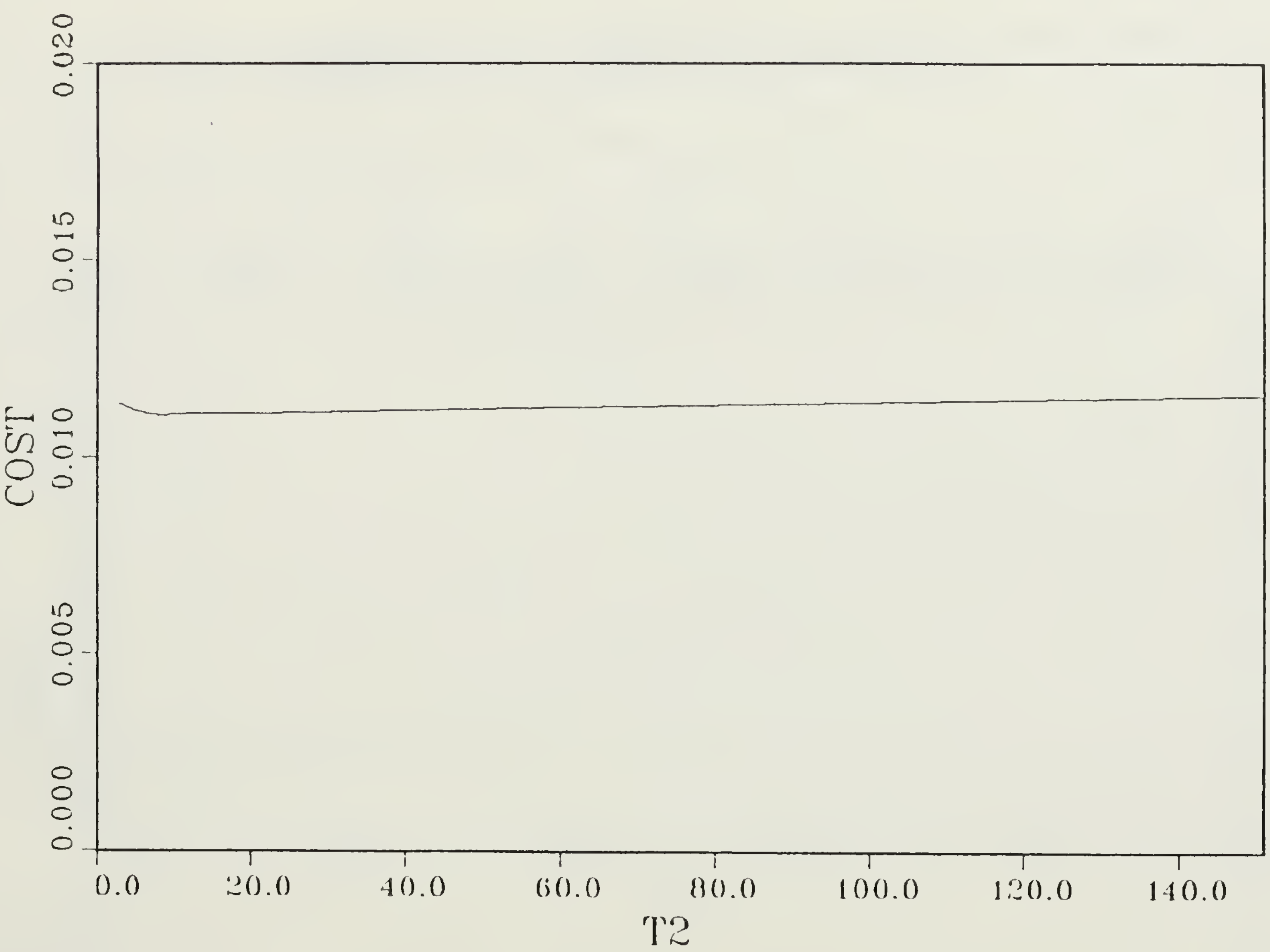

Figure 4.13 Cost vs T2, Sea State 6.
Encounter Frequency 1.5 rads per sec, Encounter Angle 120°

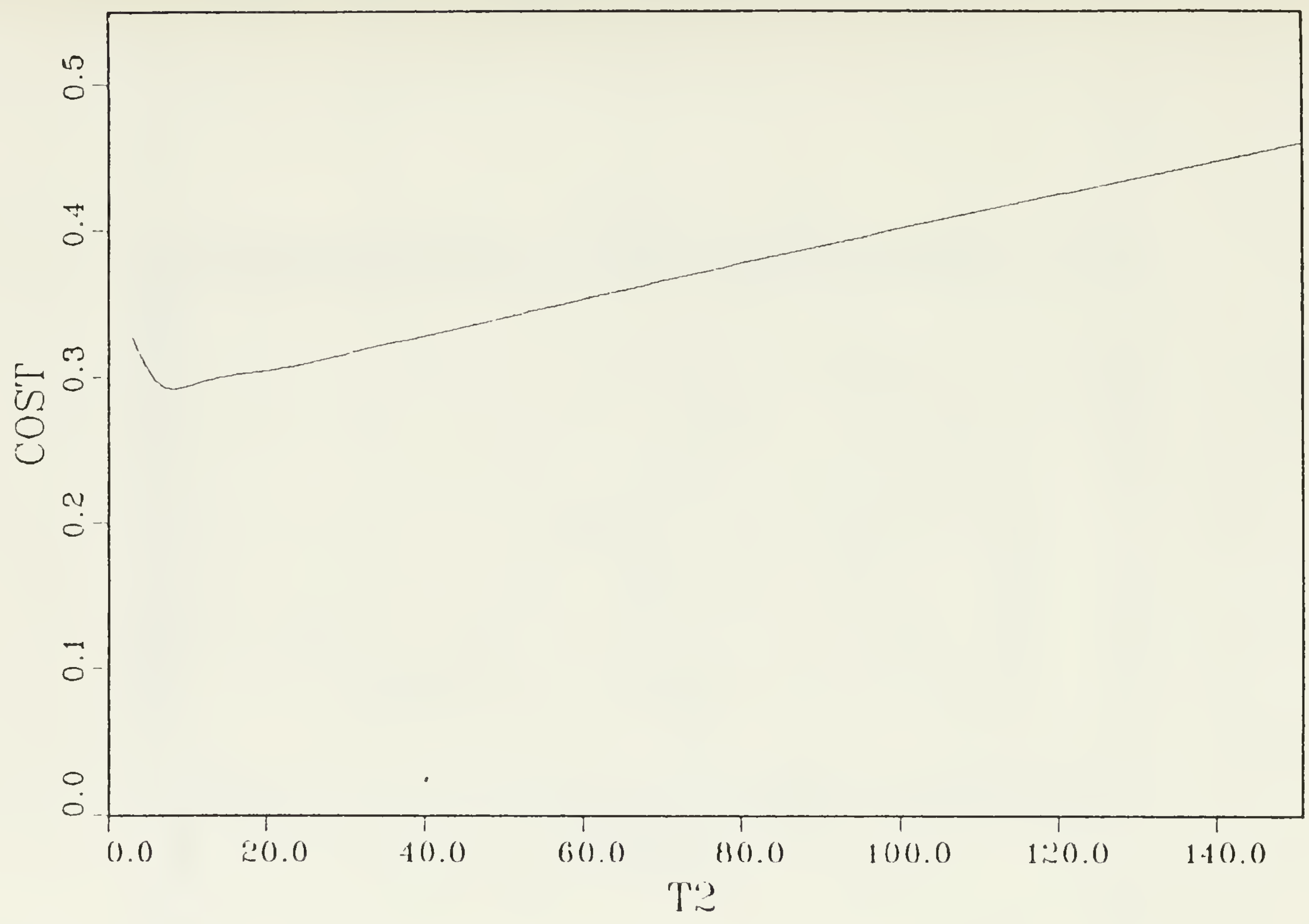

Figure 4.14 Cost vs T2, Sea State 6.
Encounter Frequency 0.6 rads per sec, Encounter Angle 90°

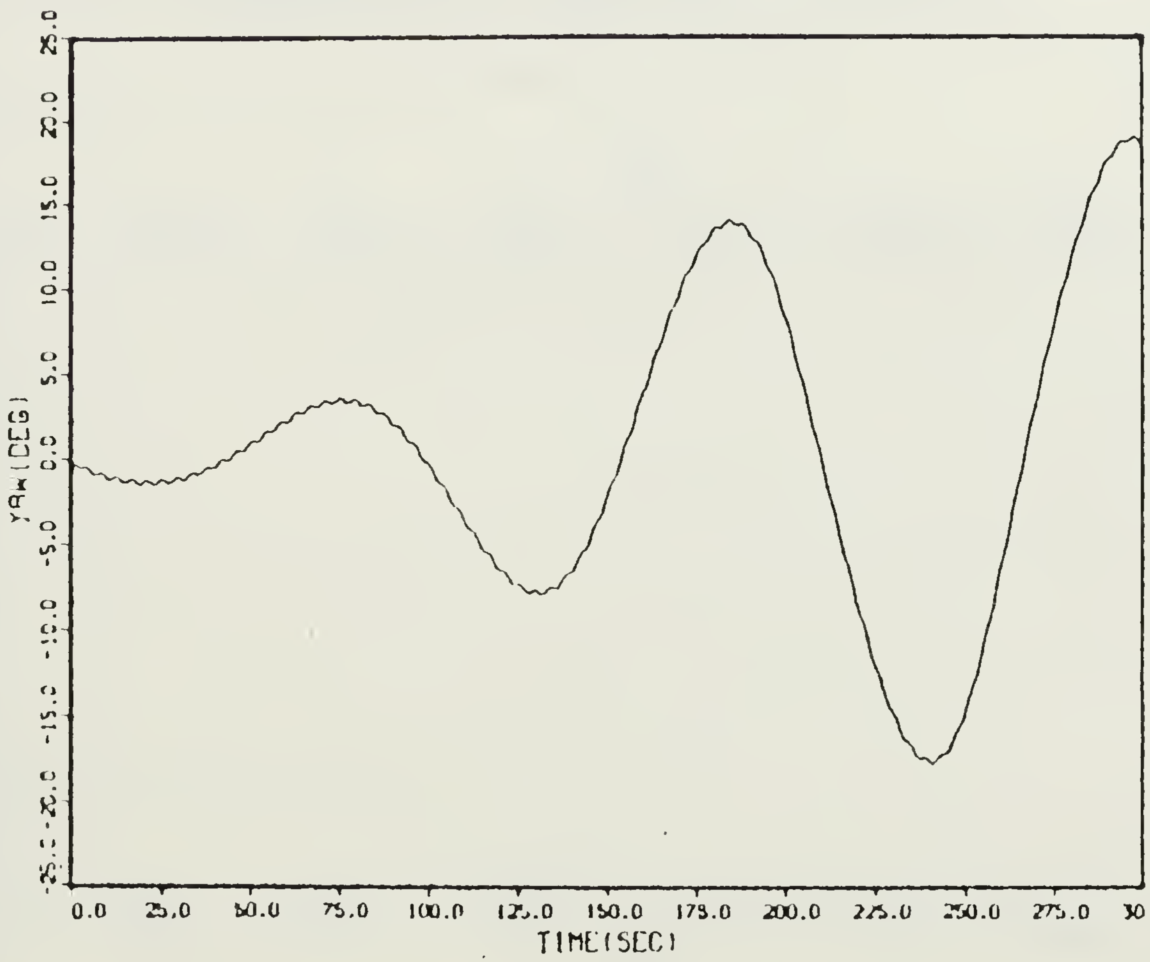

Figure 4.15 Yaw vs Time. Sea State 4, Frequency 0.4, Angle 60°. Filter for Sea State 9, Frequency 1.5, Angle 120°.

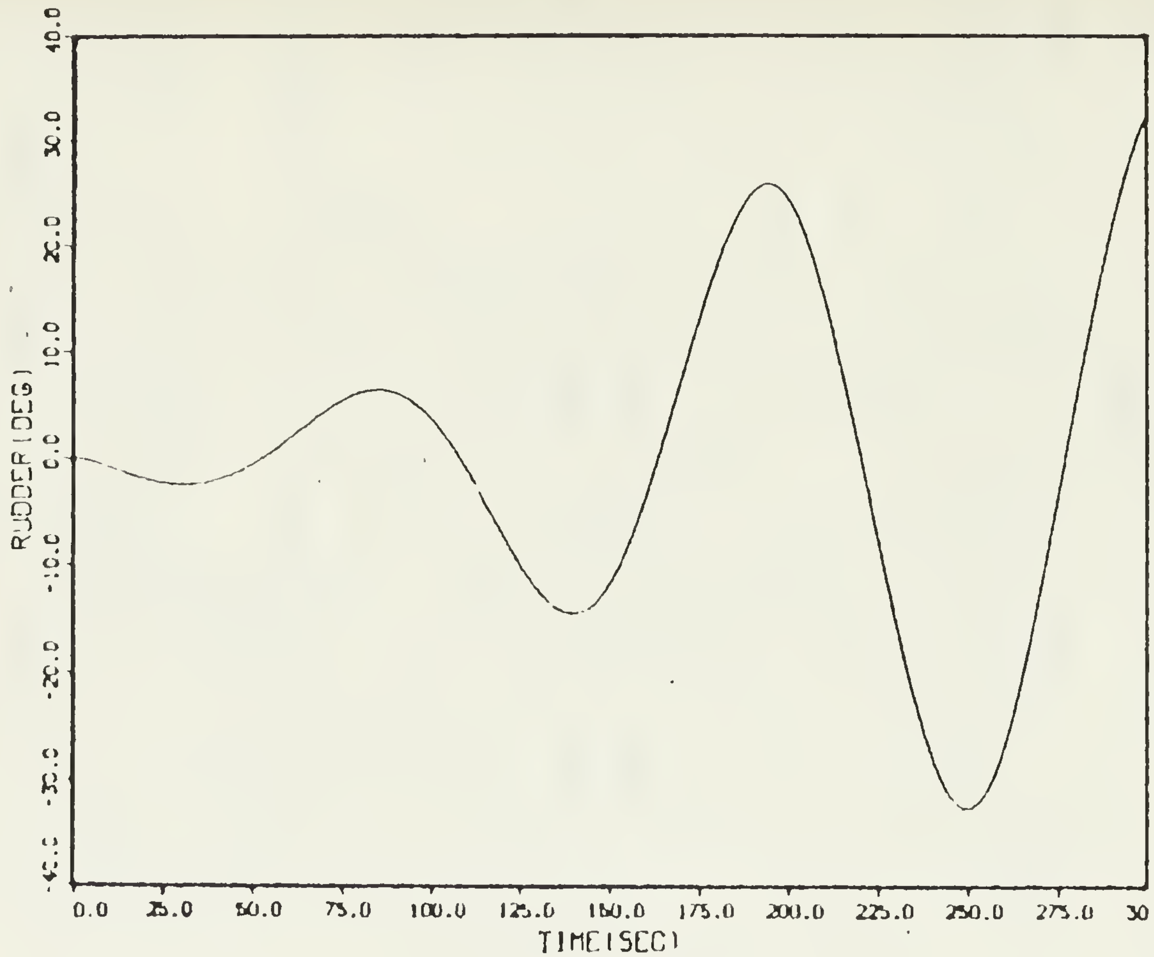

Figure 4.16 Rudder vs Time, Sea 4, Frequency 0.4, Angle 60°.
Filter for Sea State 9, Frequency 1.5, Angle 120°.

V. IRREGULAR SEAS - CONTROLLER DESIGN

The major characteristic of the sea is its irregularity. This irregularity can be described by statistical methods by assuming that a large number of regular (sinusoidal) waves having different wavelengths, directions, phases and amplitudes are superimposed to form the randomly varying sea.

The presence of the irregular sea was obtained by coupling a sea state generator program to the FORTRAN program as is indicated in Appendix D. The sea state generator program generates added mass and added inertia values as function of the encounter frequency and also calculates forces and moments imparted to the shiphull by the sea. The forces and moments are stored in a look up table which was coupled to the equations of motion. The irregular sea waves impinging on the ship contain the total energy density spectrum composed of many frequencies and the ship responds to an average value of added mass and added inertia, while in the regular sea the added mass and added inertia were known for a given encounter frequency. We decided to use values for added mass and added inertia corresponded to encounter frequency 0.75 rads per sec, since the energy density is maximum in the vicinity of this frequency [Ref. 5]. This frequency gave us values representative of an average value for added mass and added inertia.

The controller used for this study was the controller described in Chapter 4 (Figure 4.1). The optimized controller parameters and the cost J for sea states 4, 6, 7, 9 and 0°, 30°, 60°, 90°, 120°, 150°, 180° encounter angles are indicated in Table IX.

Studying the Table IX we can draw the following conclusions:

- For sea states 6, 7, 9, the higher the sea state the higher the cost, for every particular encounter angle.
- Comparing costs for sea states 4 and 6 we discover some anomaly. The cost for a specific encounter angle in sea state 4 is higher than the cost for the same encounter angle in sea state 6. Logically, we expect higher cost for higher sea state.
- The reason for this anomaly may be the method we used in order to obtain the added mass and added inertia values. The average, we consider, might not represent the actual average.

Appendix E provides the computer program necessary to achieve the system's response. Some typical responses are indicated in Figures 5.1, 5.2, 5.3, 5.4.

TABLE IX

Optimal Controller Parameters for Random Sea

Sea State 4

encounter angle(degrees)	K1	T1	T2	J
0	0.6021814	60.30849	10.02579	0.342E-24
30	1.5121580	89.85324	19.85960	0.10719
60	0.6298036	79.07199	10.29221	0.054196
90	0.6452737	82.68692	10.79342	0.076713
120	0.7485995	85.77544	12.37746	0.137624
150	0.9101038	92.71379	15.21078	0.012319
180	0.6021814	60.30849	10.02579	0.189E-28

Sea State 6

encounter angle(degrees)	K1	T1	T2	J
0	0.6021814	60.30849	10.02579	0.172E-34
30	1.8743490	61.82320	32.22498	0.044758
60	0.8662014	90.72922	14.44058	0.028238
90	0.7370305	84.08502	12.17457	0.018541
120	2.6737600	138.06650	48.52447	0.065028
150	0.4874309	77.86977	41.73848	0.012478
180	0.6021814	60.30849	10.02579	0.767E-23

Sea State 7

encounter angle(degrees)	K1	T1	T2	J
0	0.6021814	60.30849	10.02579	0.142E-34
30	1.7232471	66.44597	27.32489	0.41237
60	1.8508301	91.39410	36.91092	0.377894
90	3.7642412	62.27244	86.58169	0.258193
120	1.8482047	99.64923	91.28040	0.225806
150	0.8519831	67.02328	64.96774	0.037724
180	0.6021814	60.30849	10.02579	0.811E-21

Sea State 9

encounter angle(degrees)	K1	T1	T2	J
0	0.6021814	60.30849	10.02579	0.711E-35
30	3.1908160	138.56101	71.44171	1.306741
60	3.0888780	152.01630	72.66160	0.961709
90	3.2440700	121.13566	105.98480	0.523769
120	1.5461040	111.49130	99.64659	0.2101076
150	0.3758357	73.88629	35.17305	0.5007348
180	0.6021814	60.30849	10.02579	0.121E-31

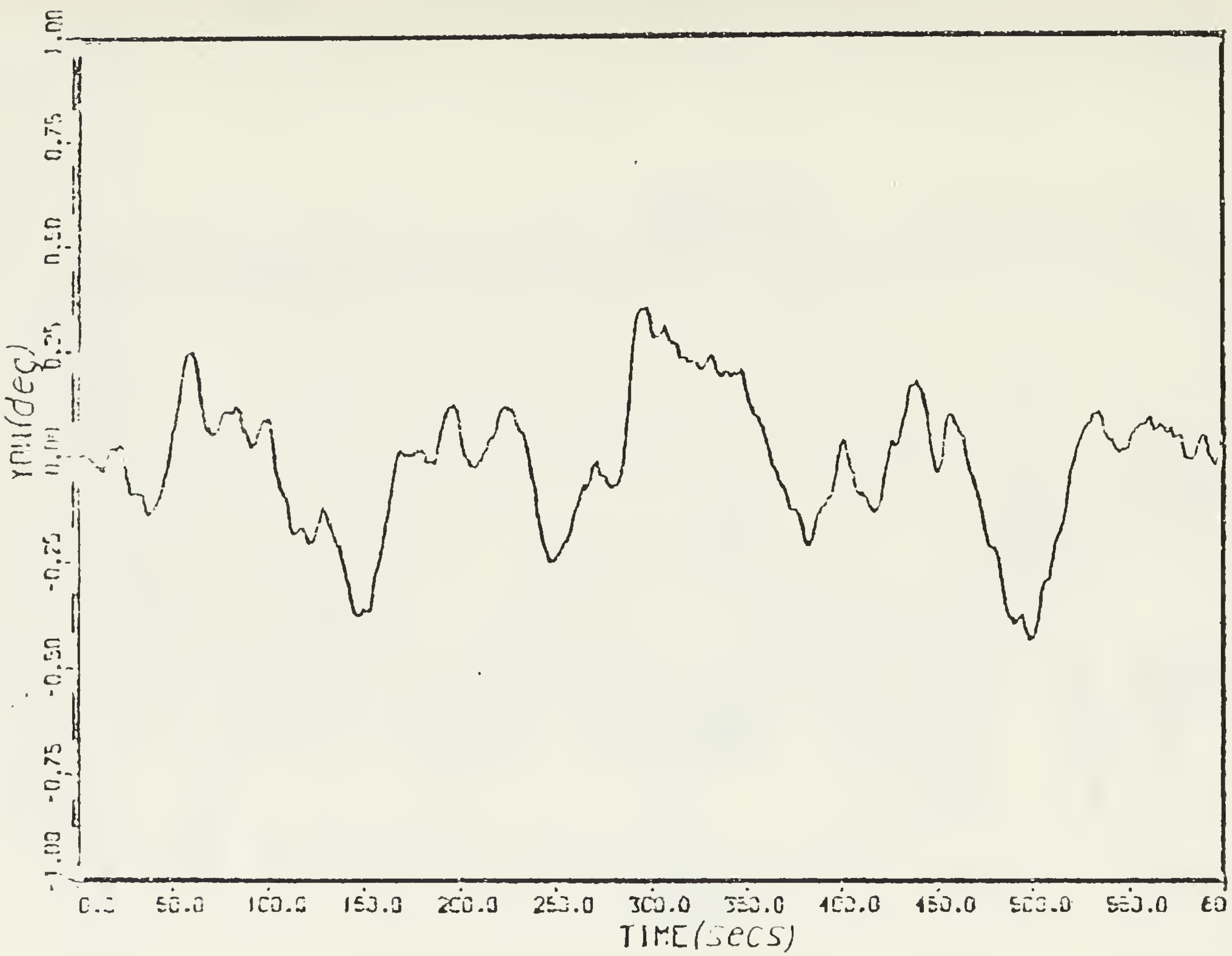

Figure 5.1 Yaw vs Time, Sea state 6. Encounter Angle 60°.

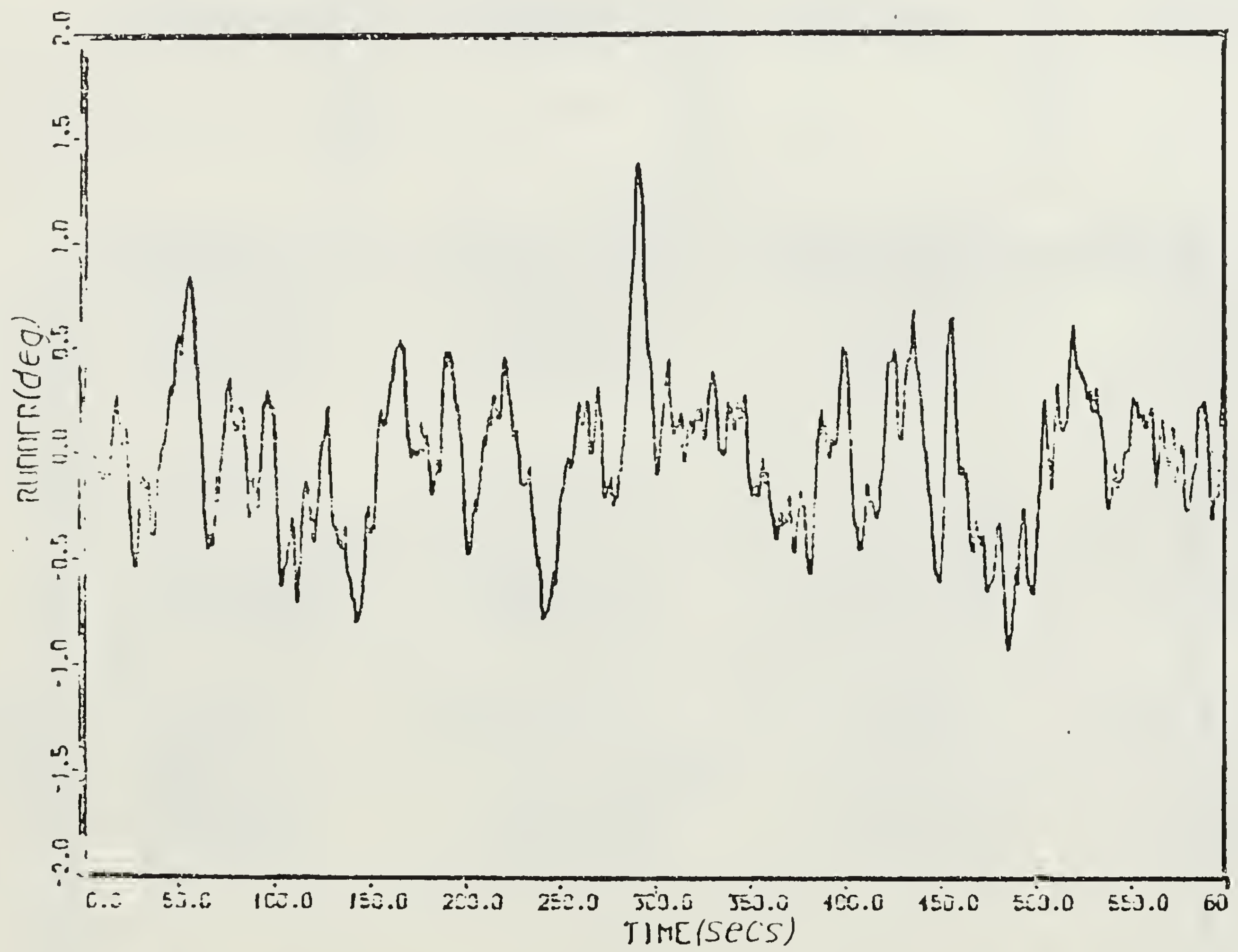

Figure 5.2 Rudder vs Time, Sea State 6.
Encounter Angle 60°.

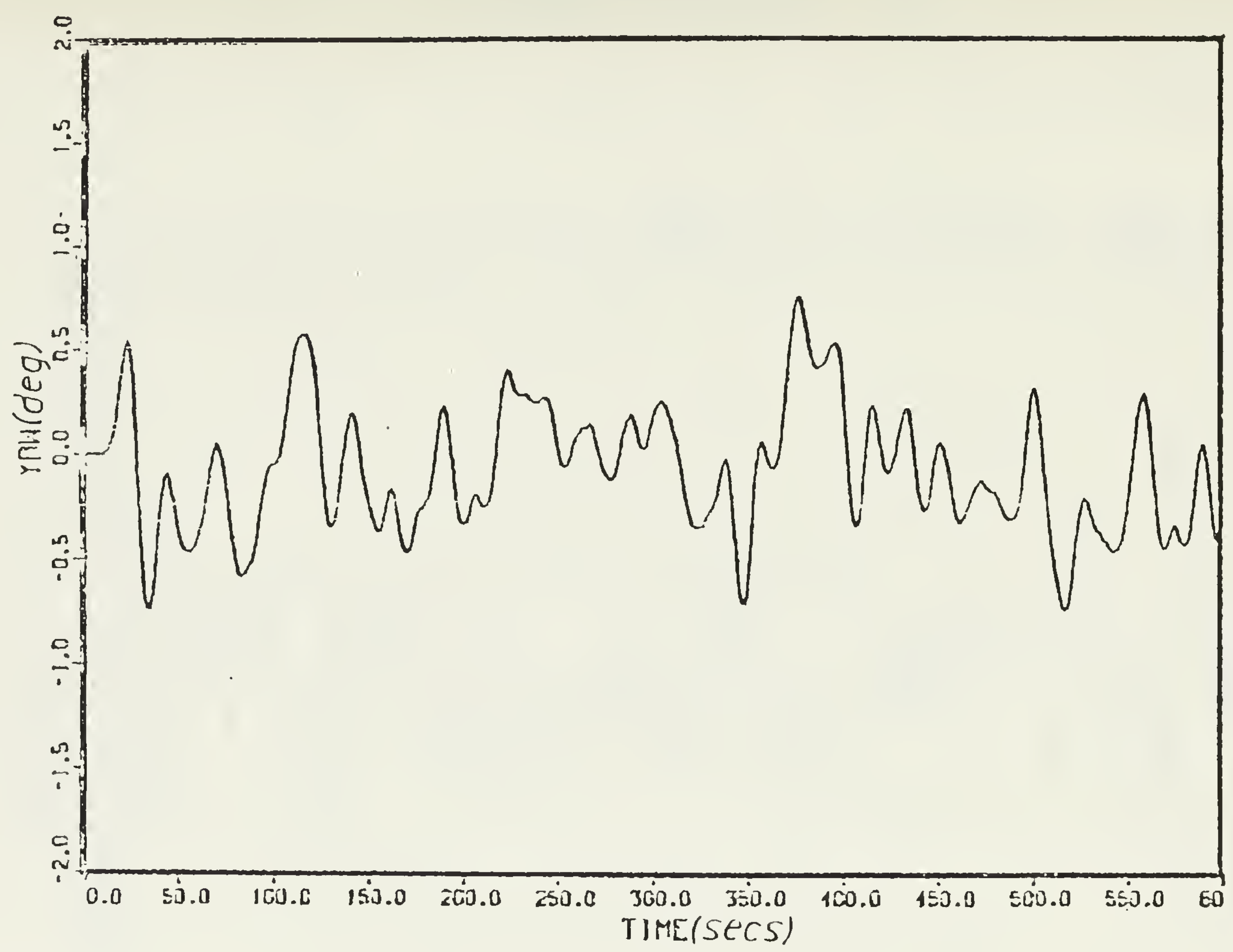

Figure 5.3 Yaw vs Time, Sea State 7.
Encounter Angle 60°.

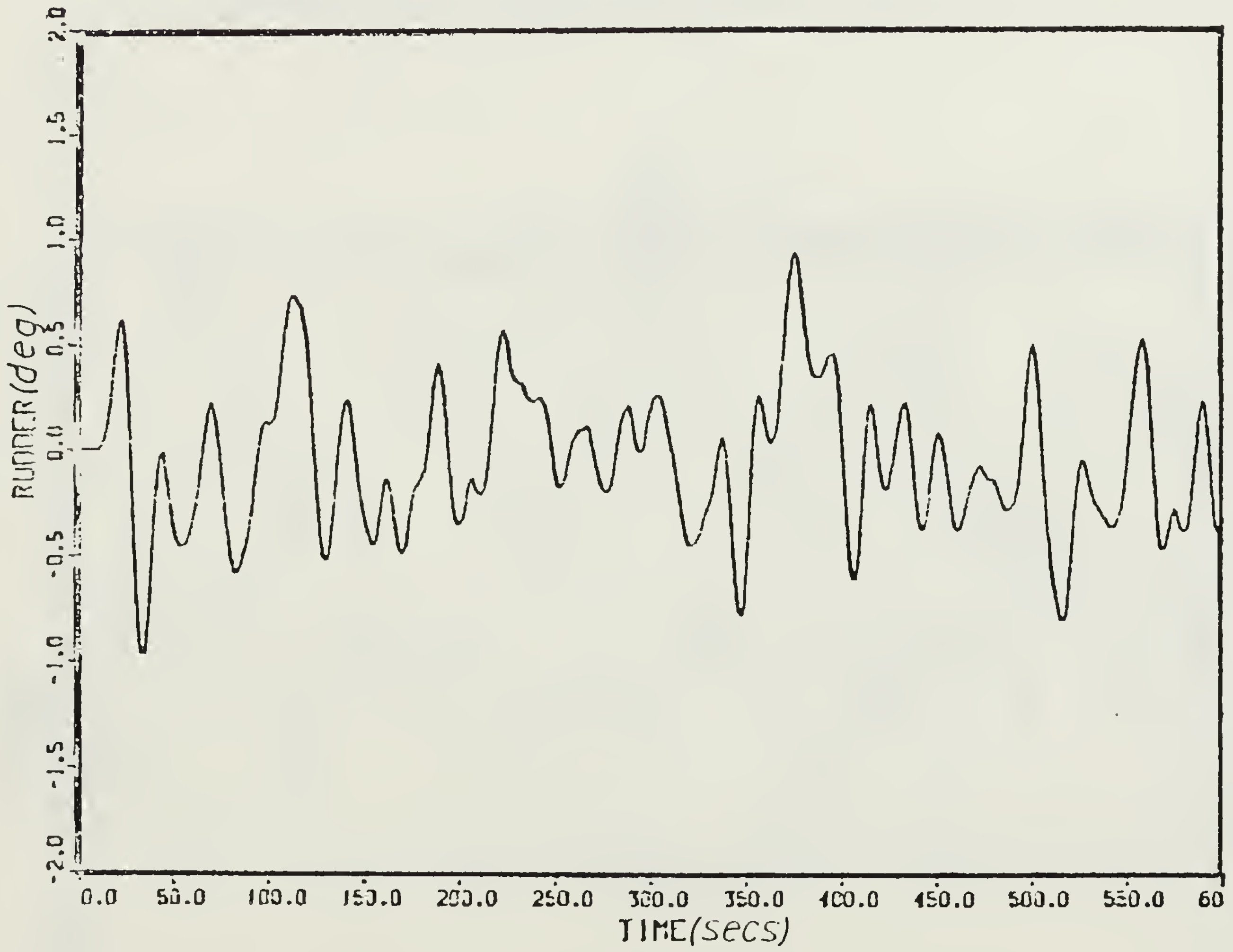

Figure 5.4 Rudder vs Time, Sea State 7. Encounter Angle 60°.

VI. MINIMIZATION SUBROUTINE FOR ONBOARD USE

A. GENERAL

As is mentioned earlier in Chapter 1 the function minimization subroutine used for these studies was BOXPLX. This subroutine will find the minimum of any function, linear or nonlinear, subject to explicit constraints of the variables or implicit constraints on functions of the variables. It will handle a maximum of 25 variables but can handle up to 50 variables with user modification.

The variables in BOXPLX are allowed to move within a feasible region (n-dimensional space, where n is the number of variables) defined by upper and lower bounds on their values. The choices for upper and lower bounds for the parameters are based on an understanding of the function of each coefficient of the system. Experience indicates that while accurate selections of these bounds are not necessary, intelligent selection of these as well as the starting values (guesses) can considerably reduce the computer number of trials needed for solution convergence. This conclusion was drawn trying to obtain the controller parameters for Tables V, VI, VII, VIII in Chapter 4. The function minimization subroutine, when starting the minimization process with arbitrary chosen guesses, required more than 100 trials for convergence while by choosing guesses close to the optimal parameters required more than 50 and less than 100 trials. Considering that every trial lasted 600 seconds (10 minutes) and the function minimization subroutine requires about 60 samples (trials) before telling us it had found the minimum this would mean 10 hours for the control to adjust itself. For obvious reasons, such operation is not acceptable for on board use.

For obvious reasons, such operation is not acceptable for on board use.

B. ATTACKING THE PROBLEM

We started to investigate ways to improve this. These efforts include:

- Finding a more efficient function minimization subroutine
- Studying the flatness of the cost surface
- Reducing sampling time

C. SOLVING THE PROBLEM

Switching to another function minimization subroutine we found that the new one (ZXMWD) suffered from the same disadvantages.

The experiments carried out, more than two hundred, indicated that the cost surface is really flat. The BOXPLX after a few trials started to focus on the minimum but before it converged, it needed more than 50 trials, even if the guesses were close to the optimal. The reason is the way BOXPLX itself tries to find the minimum of a function of NV variables. It converges when the cost FE remains unchanged for 2*NV consecutive trials with accuracy 10^{-6}. An effort to modify this termination criterion in terms of the consecutive trials was successful. Table X indicates the comparison between modified and unmodified BOXPLX, for sea state 6, encounter frequency 1.5 rads per sec and encounter angle $120°$. As we can observe in Table X the cost in each case remains almost the same while the trials required for convergence are dependent on the guesses made and the termination criterion established.

The value of the cost is in general the summation of incremental contributions for each integration step and is

TABLE X

First Modification in BOXPLX

BOXPLX	Guesses	Trials	Termination Criterion	Cost
Unmodified	Arbitrary	100	6	0.01146720
Unmodified	Optimal	72	6	0.01146720
Modified	Arbitrary	42	3	0.01146812
Modified	Optimal	11	3	0.01146720
Modified	Arbitrary	7	2	0.01157926
Modified	Optimal	1	2	0.01146720

therefore dependent on the total time of the simulation. This is important in that the optimal gain coefficients arrived at in this manner are not optimal for steady-state performance but only for the time frame covered. This should be adequate provided the time frame selected is long relative to the time required for the initial condition response to die out. This is the reason Reid has chosen time frame 600 seconds [Ref. 1,2]. Of course this time period is large and we expect steady-state behaviour faster than 10 minutes. Simulation studies indicate that the ship, controlled by the controller described in Figure 4.1, reaches the steady-state situation in less than 100 seconds. So, we can reduce the 600 seconds time frame to 200 seconds, safely. This is very important since now the modified function minimization subroutine BOXPLX, uses samples of 200 seconds long instead of 600 seconds, converges in less than 30 minutes which is reasonable for on board use. Since the value of the cost is dependent on the time frame taken we expect reduced cost for 200 seconds samples long, in any case.

As we discussed earlier the BOXPLX compares the consecutive trials with accuracy 10^{-6}. Since we do not need so big accuracy a second modification is necessary. We decided to change the existing accuracy to 10^{-4}.

Table XI indicates the trials required for BOXPLX convergence, after the second and last modification, for sea

TABLE XI

Second Modification in BOXPLX

Guesses	Trials	Termination criterion	Cost
Arbitrary	17	3	0.003999837
Optimal	8	3	0.003995277
Arbitrary	5	2	0.004024354
Optimal	1	2	0.003995247

state 6, encounter frequency 1.5 rads per sec and encounter angle 120°. By comparing Tables X and XI we can see the further improvement for the function minimization subroutine convergence. The difference in the cost is due to the different time frames used. The modified function minimization subroutine BOXPLX is indicated in Appendix F.

VII. ADAPTIVE CONTROL

A. NECESSITY OF ADAPTIVITY

The plant, the system which is supposed to be controlled, is normally exposed to a time varying environment. The ship's speed, the wave encounter angle and the sea state are changing drastically during the seaway. Since changes encountered are not completely predictable an optimum preprogrammed time-varying controller is not possible.

If we assume-and it is apparent from the previous discussion in this study-that no feasible fixed parameter controller provides acceptable response over the entire performance spectrum, it is necessary that some means is provided for adjusting controller parameters according to the sea conditions and ship's operational characteristics. Adaptive control is thus an effort to extend basic optimum control concepts to these studies.

B. CANDIDATE ADAPTIVE SCHEMES

Since we are looking for 1% or 2% savings in fuel cost, we have to feed the system with precise information. Exact knowledge of the sea state, the wave encounter angle and the ship's ground speed is vital for this purpose. Currently the Navy is involved in a program that will provide precision navigation data. Garcia [Ref. 5], provides very good information on this subject.

An adaptive control scheme is indicated in Figure 7.1. Once the adaptive part of the scheme is set up the sea state, encounter wave angle and ship's speed are fed to the filters box by the appropriate sensors. The filters box

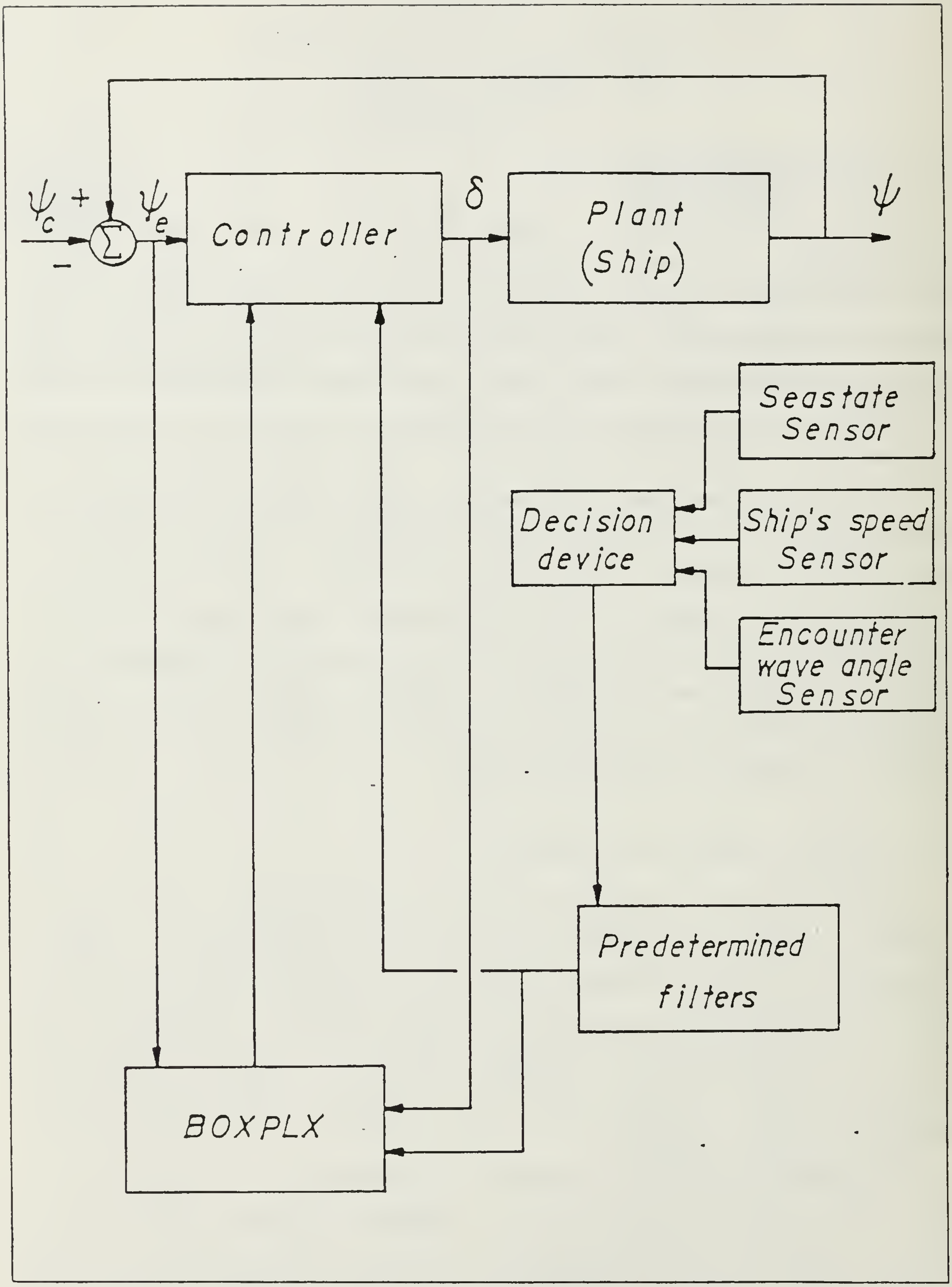

Figure 7.1 Adaptive Control Scheme

includes predetermined optimal filter sets for different discrete sea states, wave angles and ship's speed. Actually, it is a look up table similar to those of Tables V, VI,VII and VIII. The output of the filter's box is a filter which corresponds to discrete conditions close to those fed by the sensors. The function minimization subroutine accepting the rudder angle, yaw error and the predetermined filter set as initial guesses tries to obtain the optimal filter for the exact sea state, wave encounter angle and ship's speed. At the same time the plant is controlled by the controller with the optimal predetermined set of parameters for conditions close to the actual. When the function minimization subroutine reaches the minimum, it supplies the controller with a new set of parameters which is the optimal set for the present conditions.

But, what happens if either some or all the sensors provide new inputs to the system? A decision device placed after the sensors decides whether or not the change is appreciable. This device compares the current conditions with those used to obtain the controller which currently governs the system. If the change is higher than some desired percentage then a new predetermined filter is passed to the controller and the function minimization subroutine tries to find the optimal controller parameters for the new situation.

From the scheme of Figure 7.1 we can eliminate the predetermined filters device which provides a less expensive system. In this case the function minimization subroutine will need a much longer time to determine the optimal filter for rapid changes in course and speed, even if we assume that rapid changes in sea state don't occur. Finally, the function minimization subroutine might work continually "on line" as is indicated in Figure 7.2. In this scheme a new controller set is obtained in every subroutine iteration and

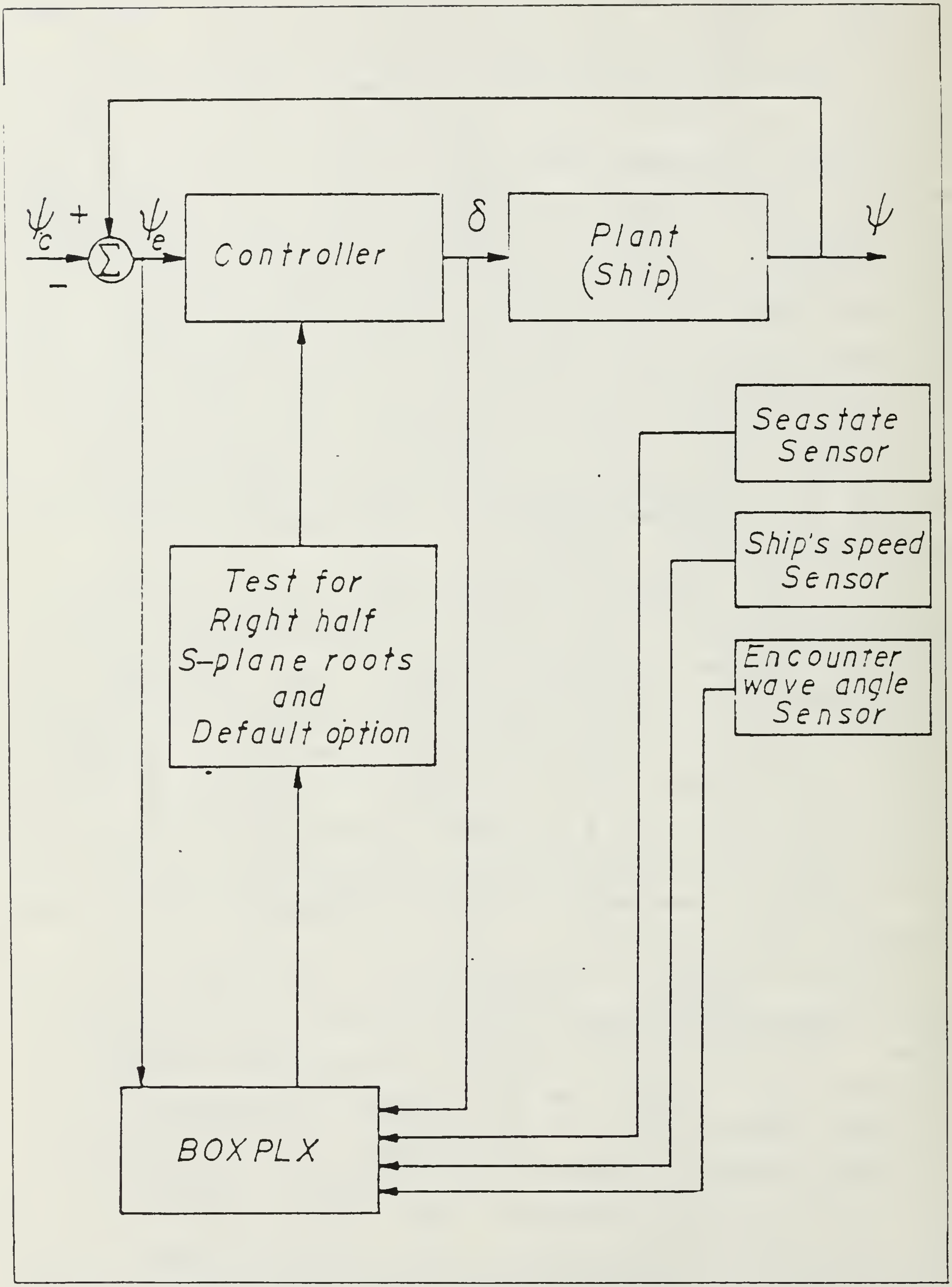

Figure 7.2 On Line Adaptive Scheme

some constraints for the controller parameters are necessary in order to avoid operation in unstable regions. Thus, the filter supplied by the subroutine for controlling the plant must be tested for characteristic equation roots in the right half S-plane. In that case a default option must exist, and a special device for such purposes is necessary. This device will permit change in the filter parameters only when the new set still keeps the system in a stable situation.

Whichever adaptive scheme we adopt, we must provide for manual operation for the system. Manual operation will be desired in the following cases:

- Arriving ports
- Leaving ports
- Restricted waters
- Avoid collision in open seas
- Computer down

For the first two situations, since we usually expect no heavy seas, the optimal filter for sea state 1 seems to be more suitable. Also, this filter can serve as initial condition for the adaptive schemes described before, when we are leaving ports. For the rest of the situations the last operating optimal filter is the most appropriate.

VIII. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The principal conclusions from this study of the SL-7 containership as they related to steering may be stated as follows:

- It is evident that a control system which provides the ship heading and simultaneously reduces the propulsive losses does exist and therefore such a controller saves fuel. We can't conclude how much the savings are, since there is no reference for comparison between the conventional autopilot and the autopilot which, in addition, holds the potential for reducing the propulsive losses. The literature says that savings 1% or 2% is possible.
- An adaptive controller, that minimizes propulsion losses as ship characteristics and environmental conditions change, may be designed using a self-optimalizing technique employing a suitable performance criterion.
- Studying every particular situation we conclude that the cost surface is flat and therefore accurate determination of the controller parameters is not required. So, if we decide to use the adaptive control scheme of Figure 7.1 we don't have to store every particular filter in the look up table since one filter may be suitable for different ship characteristics and sea conditions.
- The weighting factor λ used in the performance criterion equation 3.5 plays an exceptional and important role in the optimal controller parameters determination. However, it is obtained from studies based on

many assumptions and therefore isn't predicted accurately. As a consequence the controller found does not minimize added resistance unless the proper value of the weighting factor λ has been used.

- The method used to obtain the average for the added mass and added inertia for the irregular seas studies might not represent the actual average.
- The function minimization subroutine BOXPLX after two modifications seems to be pretty suitable for on board use working as a main part of the adaptive scheme.

B. RECOMMENDATIONS FOR FUTURE STUDIES

The following recommendations for future work to gain a fuller and deeper understanding of the problem are made as follows:

- Some studies are necessary in order to investigate why part of the obtained controllers in Tables V, VI, VII, VIII are lag and part of them are lead filters.
- As we stated in chapter 4 the yaw and rudder excursions in Figures 4.2 through 4.9 are less than 1°. It is necessary to investigate the reason for that. It might be because of the optimization of the filter or the forces and moments have not been sealed properly.
- It is necessary to find out the appropriate average values for the added mass and added inertia before we attempt further studies in irregular seas.
- The full hydrodynamic coefficients for the SL-7 are necessary in order to develop and include the surge equation in our ship model. So far we ignore the surge equation and we assumed constant ship speed while in reality the added resistance due to steering must reduce the ship speed.

- By developing the surge equation in our ship model we may be able to determine a good value for the weighting factor to be used in the performance criterion.
- Also, with the surge equation available in our model we should be able to calculate actual energy losses and savings in fuel.
- As we stated in chapter 6 the time frames (samples) used by the BOXPLX must be long relative to the time required for the initial condition response to die out. Reid [Ref. 1,2] has chosen time frame 600 seconds long. This time frame is long and it is necessary to find out the sufficient time frame since the time required by the function minimization subroutine for convergence is directly proportional to the sample duration.

APPENDIX A

NOMOTO THIRD ORDER MODEL DETERMINATION

```
//NOMOTO JOB (XXXX,XXXX),'RESEARCH',CLASS=J
//*MAIN ORG=NPGVM1.XXXXP
// EXEC FORTXCG,PARM.FORT='OPT(2)',IMSL=DP,REGION=1024K
//FORT.SYSIN DD *
C  IN ORDER TO PERFORM SIMULATION ONLY WHEN GAINS HAVE BEEN
C  OBTAINED CHANGE XS(*) TO X(*) AND DELETE XU(*),AND XL(*)
      DIMENSION XS(4),XU(4),XL(4)
      XS(1)=0.1
      XS(2)=15.13
      XS(3)=15.675
      XS(4)=9.014
C  XS(I) IS THE STARTING GUESS
C  XL(I) IS THE LOWER LIMIT FOR THE I'TH VARIABLE
C  XU(I) IS THE UPPER LIMIT FOR THE I'TH VARIABLE
      XL(1)=.01
      XU(1)=1.0
      XL(2)=1.0
      XU(2)=20.
      XL(3)=1.0
      XU(3)=100.
      XL(4)=1.0
      XU(4)=100.0
C  A DESCRIPTION OF THE FOLLOWING PARAMETERS
C  IS DISCUSSED IN BOXPLX
      R=9./13.
      NTA=1000
      NPR=0
      NAV=0
      NV=4
      IP=0
```

```
C  THE FOLLOWING STATEMENT MUST BE CHANGED TO
C  CALL PLANT(XX)
C  IF ONLY SIMULATION IS WANTED
      CALL BOXPLX(NV,NAV,NPR,NTA,R,XS,IP,XU,XL,YMN,IER)
      WRITE (6,25)
 25   FORMAT(1X,' OPTIMAL GAINS',/)
      DO 30 I=1,4
 30   WRITE(6,40)I,XS(I)
 40   FORMAT(1X,'X(',I2,')=',F14.7)
      WRITE (6,77) TDIFF
 77   FORMAT(1X,'COST=',F14.7)
      STOP
      END
C  SUBROUTINE PLANT(XX) SIMULATES THE SHIP
      SUBROUTINE PLANT(XX)
      COMMON TDIFF
      REAL*8 L,L2,L3,L4,L5,L6,RXR,RXI,RYR,RYI,MZR,MZI,RX,RY
      REAL*8 X,XDOT,Y,YDOT,U,UDOT,V,VDOT,YAW,R,RDOT,TX,TY
      REAL*8 TIME,ETIME,XUDOT,XU,XUU,XVR,XVV,XDD,WA,WE,RZ
      REAL*8 YV,YR,YD,YVVR,YVRR,YVVV,YRRR,YDDD,YVDOT,TZ
      REAL*8 NV,NR,ND,NVVR,NVRR,NVVV,NRRR,NDDD,NRDOT
      REAL*8 RHO,IZ,FX,FY,MZ,XP,MASS,DELT
      REAL*8 YAWE,YAWC,D2,D
      REAL*8 K,TP1,TP2,Z,X1,X2,X3,X4,X5,YAW2,S
      DIMENSION XX(4)
C  INITIAL CONDITIONS FOR INTEGRATION
C  SIMULATION END TIME IN SECONDS
      ETIME=600.
      TIME=0.0
      ICOUNT=1
C  INITIALIZE THE COST FUNCTION
      TDIFF=0.0
C  GAIN COEFFICIENTS TO BE OPTIMIZED
      K=XX(1)
      Z=XX(2)
```

```
      TP1=XX(3)
      TP2=XX(4)
C  X,XDOT,Y,YDOT ARE FIX COORDINATES ON EARTH
      X=0.0
      Y=0.0
      XDOT=0.0
      YDOT=0.0
C  U,UDOT,V,VDOT ARE FIX COORDINATES ON SHIP
      V=0.0
      UDOT=0.0
      VDOT=0.0
      YAW=0.0
      R=0.0
      RDOT=0.0
C  ORDERED SPEED IN  FEET/SEC
C  38.81 FT/SEC=23 KNOTS
      UC=38.81
C  AT STEADY STATE ACTUAL SPEED (U) = COMMAND SPEED (UC)
      U=UC
C  D = RUDDER ANGLE
      D=0.0
      L=880.5
      L2=L**2
      L3=L*L*L
      L4=L*L3
      L5=L*L4
      L6=L*L5
C  SEA DISTURBANCE
C  FORCES IN X,Y DIRECTION COMPUTED IN FORCES
C  MOMENTS IN Z
      FX=0.0
      FY=0.0
      MZ=0.0
C     RXR=-.15744D+05
C     RXI=-.19950D+06
```

```
C     RYR=0.52365D+04
C     RYI=0.18699D+06
C     MZR=-.29870D+08
C     MZI=-.37751D+07
      RXR=-.50230D+04
      RXI=0.12712D+05
      RYR=0.35290D+04
      RYI=-.31909D+05
      MZR=0.38826D+07
      MZI=-.64313D+07
C     RXR=0.28540D+04
C     RXI=-.99574D+04
C     RYR=-.85441D+04
C     RYI=0.39595D+05
C     MZR=-.13014D+08
C     MZI=0.11348D+08
C     RXR=-.75642D+04
C     RXI=0.83497D+04
C     RYR=0.23379D+05
C     RYI=-.81502D+05
C     MZR=0.28622D+07
C     MZI=-.19388D+08
C     RXR=-.37916D+04
C     RXI=0.16381D+04
C     RYR=-.76647D+05
C     RYI=-.37685D+05
C     MZR=-.83915D+07
C     MZI=-.53176D+07
      RX=DSQRT(RXR**2+RXI**2)
      RY=DSQRT(RYR**2+RYI**2)
      RZ=DSQRT(MZR**2+MZI**2)
      TX=DATAN2(RXI,RXR)
      TY=DATAN2(RYI,RYR)
      TZ=DATAN2(MZI,MZR)
C  SIGNIFICANT WAVE HEIGHT; SEA STATE 1-0.32,2-0.75,3-2.5,
```

```
C  4-5.0,5-7.0,6-10.0,7-17.5,8-20.5,9-27.0
      WA=10.0
C  ENCOUNTER FREQUENCY .1,.2,.3,.4,.5,.6,.75,1.0,1.5,2.5
      WE=0.4
C  HYDRODYNAMIC COEFFICIENTS ARE INSERTED AS PARAMETERS
      RHO=1.9876
      MASS=(.0044)*(.5*RHO*L3)
      IZ=(0.00028)*(.5*RHO*L5)
      YAWE=0.0
      X1=0.0
      X2=0.0
      X3=0.0
      X4=0.0
      X5=0.0
      YAW2=0.0
  200 CONTINUE
      S=DSQRT(U**2 + V**2)
C  INPUT YAW COMMAND
      YAWC=0.0
      IF (TIME.GE.0.0) YAWC=(1.0/57.296)
C  ERROR SIGNAL TO DRIVE RUDDER (YAW ACTUAL - YAW COMMAND)
C  FOR EQUATIONS OF MOTION.
      YAWE=YAW - YAWC
      D=YAWE
C
C    NOMOTO 3RD ORDER PLANT
C
C  ERROR SIGNAL TO DRIVE RUDDER (YAW COMMAND - YAW ACTUAL)
C  FOR NOMOTO MODEL.
      D2=YAWC-YAW2
      X1=(D2-X2)/TP1
      X3=K*(Z*X1+X2)
      X4=(X3-X5)/TP2
C  AXIAL FORCE HYDRODYNAMIC COEFFICIENTS (SURGE)
      XUDOT=(-.0001)*(.5*RHO*L3)
```

```
      XUU=(-0.0003)*(.5*RHO*L2)
      XU=(-0.0253)*(0.5*RHO*L2*S)
      XVR=(0.0039)*(.5*RHO*L3)
      XVV=(-.0012)*(.5*RHO*L2)
      XDD=(-0.0005)*(.5*RHO*L2*S**2)
C  LATERAL FORCE HYDRODYNAMIC COEFFICIENTS (SWAY)
C     YV=(-0.00758)*(.5*RHO*L2*S)
      YR=(0.0023)*(.5*RHO*L3*S)
      YD=(0.00145)*(.5*RHO*L2*S**2)
      YVVR=(0.01)*(.5*RHO*L3/S)
      YVRR=(-0.008)*(.5*RHO*L4/S)
      YVVV=(-0.03)*(.5*RHO*L2/S)
      YRRR=(0.003)*(.5*RHO*L5/S)
      YDDD=(-0.0005)*(.5*RHO*L2*S**2)
      YVDOT=-0.30908D+07
      YV=-0.81271D+04
C     YVDOT=-.36185D+07
C     YV=-.24757D+06
C     YVDOT=-.32890D+07
C     YV=-.11775D+07
C     YVDOT=-.23038D+07
C     YV=-.18267D+07
C     YVDOT=-.59800D+06
C     YV=-.13260D+07
C  MOMENT ABOUT Z-AXIS HYDRODYNAMIC COEFFICIENTS (YAW)
      NV=(-0.00213)*(.5*RHO*L3*S)
C     NR=(-0.00105)*(.5*RHO*L4*S)
      ND=(-0.0007)*(.5*RHO*L3*S**2)
      NVVR=(-0.015)*(.5*RHO*L4/S)
      NVRR=(-0.008)*(.5*RHO*L5/S)
      NVVV=(0.01)*(.5*RHO*L3/S)
      NRRR=(-0.006)*(.5*RHO*L6/S)
      NDDD=(0.0001)*(.5*RHO*L3*S**2)
C  NRDOT IS THE ADDED INERTIA TERM WHICH MUST BE CHANGED
C  FOR DIFFERENT ENCOUNTER ANGLE,SPEED,ENCOUNTER FREQUENCY
```

```
C
C     NRDOT=(-0.00027)*(.5*RHO*L5)
C  SPEED=23 KNOTS,ENCOUNTER ANGLE = 60,ENCOUNTER FREQ=0.75
C     NRDOT=-.26251D+12
C     NR=-.53637D+09
      NRDOT=-.20125D+12
      NR=-.94970D+10
C     NRDOT=-.18671D+12
C     NR=-.46860D+11
C     NRDOT=-.14518D+12
C     NR=-.87538D+11
C     NRDOT=-.37261D+11
C     NR=-.69856D+11
C  SETS SEA STATE TO ZERO
      FX=0.
      FY=0.
      MZ=0.
      FX=WA*RX*DCOS(WE*TIME+TX)
      FY=WA*RY*DCOS(WE*TIME+TY)
      MZ=WA*RZ*DCOS(WE*TIME+TZ)
C  U ACTUAL SPEED
C  UC COMMANDED SPEED
C  XP = PROPELLER THRUST
      XP=-XUU*UC**2
C  EQUATIONS OF MOTION
C     UDOT=( (XVR + MASS)*V*R + XUU*U**2 + XVV*V**2
C    1 + XDD*D*D +  FX + XP )/(MASS-XUDOT)
      VDOT=(YV*V + (YR-MASS*U)*R + YD*D + YVVR*V**2*R
     1 + YVRR*V*R**2 + YVVV*V*V**3
     2 + YRRR*R**3 + YDDD*D**3 + FY )/(MASS-YVDOT)
      RDOT=(NV*V + NR*R + ND*D + NVVR*V**2*R + NVRR*V*R**2
     1 +NVVV*V**3 + NRRR*R**3 + NDDD*D**3 + MZ )/(IZ-NRDOT)
C  WHEN TO PRINTOUT
      IF (ICOUNT.EQ.11) GO TO 50
      GO TO 300
```

```
C  CONVERT RADIANS TO DEGREES
 50  YAWDEG= YAW*57.296
     RDEG=R*57.296
     RDDEG=RDOT*57.296
     DDEG=D*57.296
     YAWC=YAWC*57.296
     ICOUNT=1
C  TEST IF WANT TO STOP
300  IF (TIME.GE.ETIME) GO TO 400
C  INTEGRATION STEP SIZE DELT
     DELT=1.0
C  INTEGRATION
     X2=X2+X1*DELT
     X5=X5+X4*DELT
     YAW2=YAW2+X5*DELT
     U=U+UDOT*DELT
     V=V+VDOT*DELT
     R=R+RDOT*DELT
     YAW=YAW+R*DELT
C  CONVERT SHIP TO FIXED COORDINATES ON EARTH
     XDOT=U*DCOS(YAW)-V*DSIN(YAW)
     YDOT=U*DSIN(YAW)+V*DCOS(YAW)
     X=X+XDOT*DELT
     Y=Y+YDOT*DELT
     TIME=TIME+DELT
     ICOUNT=ICOUNT+1
C  COST FUNCTION
     TDIFF=TDIFF+ (YAW-YAW2)**2
     GO TO 200
400  CONTINUE
C    WRITE(6,500) TDIFF,K,Z,TP1,TP2
500  FORMAT(' ',1X,'  COST =',F12.7,2X,' K =',F10.7,
    1 ' Z =',F15.7,' TP1 =',F15.7,2X,' TP2 =',F15.7)
     RETURN
     END
```

APPENDIX B

REGULAR SEASTATE FORMULATION

```
//REGUGAINS JOB (XXXX,XXXX),'RESEARCH',CLASS=C
//*MAIN ORG=NPGVM1.XXXXP
// EXEC FORTXCG,PARM.FORT='OPT(2)',IMSL=DP,REGION=1024K
//FORT.SYSIN DD *
C  IN ORDER TO PERFORM SIMULATION ONLY WHEN GAINS HAVE BEEN
C  OBTAINED CHANGE XS(*) TO X(*) AND DELETE XU(*),AND XL(*)
      DIMENSION XS(3),XU(3),XL(3)
      XS(1)=0.9650610
      XS(2)=0.4500911
      XS(3)=5.6194260
C  XS(I) IS THE STARTING GUESS
C  XL(I) IS THE LOWER LIMIT FOR THE I'TH VARIABLE
C  XU(I) IS THE UPPER LIMIT FOR THE I'TH VARIABLE
      XL(1)=0.1
      XU(1)=4.0
      XL(2)=0.1
      XU(2)=15.0
      XL(3)=1.0
      XU(3)=25.0
C  A DESCRIPTION OF THE FOLLOWING PARAMETERS
C  IS DISCUSSED IN BOXPLX
     R=9./13.
     NTA=1000
     NPR=100
     NAV=0
     NV=3
     IP=0
C  THE FOLLOWING STATEMENT MUST BE CHANGED TO
C  CALL PLANT(X)
C  IF ONLY SIMULATION IS WANTED
```

```
      CALL BOXPLX(NV,NAV,NPR,NTA,R,XS,IP,XU,XL,YMN,IER)
      WRITE (6,25)
25    FORMAT(1X,' OPTIMAL GAINS',/)
      DO 30 I=1,3
30    WRITE(6,40)I,XS(I)
40    FORMAT(1X,'X(',I2,')=',F14.7)
      STOP
      END
      SUBROUTINE PLANT(XX)
C  SUBROUTINE PLANT(XX) SIMULATES THE SHIP
      COMMON TDIFF
      REAL*8 L,L2,L3,L4,L5,L6
      REAL*8 X,XDOT,Y,YDOT,U,UDOT,V,VDOT,YAW,R,RDOT
      REAL*8 TIME,ETIME,XUDOT,XUU,XVR,XVV,XDD
      REAL*8 YV,YR,YD,YVVR,YVRR,YVVV,YRRR,YDDD,YVDOT
      REAL*8 NV,NR,ND,NVVR,NVRR,NVVV,NRRR,NDDD,NRDOT
      REAL*8 RHO,IZ,FX,FY,MZ,XP,MASS,DELT,MZI,WA,WE
      REAL*8 DYAWE,YAWE,YAWC,ISE,ISR,LAMDA,D,RYR,RYI,MZR
      REAL*8 K1,T1,T2,D,X2,DX2,S,RX,RY,RZ,TX,TY,TZ,RXR,RXI
      DIMENSION XX(3)
C
C  CLOSE LOOP ANALYSIS WITH FILTER
C
C  INITIAL CONDITIONS FOR INTEGRATION
C  SIMULATION END TIME IN SECONDS
      ETIME=600.0
      TIME=0.0
      ICOUNT=1
C  INITIALIZE THE COST FUNCTION
      ISE=0.0
      ISR=0.0
      TDIFF=0.0
      LAMDA=8.128
C  GAIN COEFFICIENTS TO BE OPTIMIZED
      K1=XX(1)
```

```
      T1=XX(2)
      T2=XX(3)
C     WRITE(6,1010) K1,T1,T2
C1010  FORMAT(1X,'K1 =',F15.7,' T1 =',F15.7,' T2 =',F15.7)
C  X,XDOT,Y,YDOT ARE FIX COORDINATES ON EARTH
      X=0.0
      Y=0.0
      XDOT=0.0
      YDOT=0.0
C  U,UDOT,V,VDOT ARE FIX COORDINATES ON SHIP
      V=0.0
      UDOT=0.0
      VDOT=0.0
      YAW=0.0
      R=0.0
      RDOT=0.0
C  ORDERED SPEED IN  FEET/SEC
C   38.81 FT/SEC=23 KNOTS
      UC=38.81
C  AT STEADY STATE ACTUAL SPEED (U) = COMMAND SPEED (UC)
      U=UC
C  D = RUDDER ANGLE
      D=0.0
      L=880.5
      L2=L**2
      L3=L*L*L
      L4=L*L3
      L5=L*L4
      L6=L*L5
C  SEA DISTURBANCE
C  FORCES IN X,Y DIRECTION COMPUTED IN FORCES
C  MOMENTS IN Z
      FX=0.
      FY=0.
      MZ=0.
```

```
C       RXR=-0.91037D+03
C       RXI=0.50869D+05
C       RYR=-0.20256D+04
C       RYI=0.18077D+06
C       MZR=-.14310D+08
C       MZI=-.16903D+07
C       RXR=-0.99047D+04
C       RXI=.15994D+06
C       RYR=-.64455D+05
C       RYI=0.61873D+06
C       MZR=.120180+08
C       MZI=-.49204D+07
C       RXR=-0.32876D+05
C       RXI=0.25844D+06
C       RYR=-.27053D+06
C       RYI=.90191D+06
C       MZR=0.11964D+09
C       MZI=0.24103D+08
C       RXR=-.54639D+05
C       RXI=.28236D+06
C       RYR=-.28668D+06
C       RYI=0.79670D+06
C       MZR=0.19925D+09
C       MZI=0.77746D+08
        RXR=0.27268D+05
        RXI=-.71601D+05
        RYR=0.14077D+05
        RYI=-.28679D+06
        MZR=-.30892D+08
        MZI=-.53246D+08
        RX=DSQRT(RXR**2+RXI**2)
        RY=DSQRT(RYR**2+RYI**2)
        RZ=DSQRT(MZR**2+MZI**2)
        TX=DATAN2(RXI,RXR)
        TY=DATAN2(RYI,RYR)
```

```
      TZ=DATAN2(MZI,MZR)
C   SIGNIFICANT WAVE HEIGHT; SEA STATE 1-0.32,2-0.75,3-2.5,
C   4-5.0,5-7.0,6-10.0,7-17.5,8-20.5,9-27.0
      WA=10.0
C   ENCOUNTER FREQUENCY .1,.2,.3,.4,.5,.6,.75,1.0,1.5,2.5
      WE=1.5
C   HYDRODYNAMIC COEFFICIENTS ARE INSERTED AS PARAMETERS
      RHO=1.9876
      MASS=(.0044)*(.5*RHO*L3)
      IZ=(0.00028)*(.5*RHO*L5)
      YAWE=0.0
      X2=0.0
      DX2=0.0
  200 CONTINUE
      S=DSQRT(U**2+V**2)
C   INPUT YAW COMMAND
      YAWC=0.0
      IF (TIME.GE.0.0) YAWC=0.0
C   ERROR SIGNAL TO DRIVE RUDDER(YAW ACTUAL - YAW ORDERED)
C   ( COMPENSATOR FILTER )
      YAWE=YAW - YAWC
      DX2=(YAWE-X2)/T2
      D=K1*(T1*DX2+X2)
C   AXIAL FORCE HYDRODYNAMIC COEFFICIENTS (SURGE)
C   XUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED FOR
C   DIFFERENT ENCOUNTER ANGLE , SPEED , ENCOUNTER FREQUENCY
C
      XUDOT=(-.0001)*(.5*RHO*L3)
      XU=(-0.0253)*(.5*RHO*L2*S)
      XUU=(-0.0003)*(.5*RHO*L2)
      XVR=(0.0039)*(.5*RHO*L3)
      XVV=(-.0012)*(.5*RHO*L2)
      XDD=(-0.0005)*(.5*RHO*L2*S**2)
C   LATERAL FORCE HYDRODYNAMIC COEFFICIENTS (SWAY)
C     YV=(-0.00758)*(.5*RHO*L2*S)
```

```
      YR=(0.0023)*(.5*RHO*L3*S)
      YD=(0.00145)*(.5*RHO*L2*S**2)
      YVVR=(0.01)*(.5*RHO*L3/S)
      YVRR=(-0.008)*(.5*RHO*L4/S)
      YVVV=(-0.03)*(.5*RHO*L2/S)
      YRRR=(0.003)*(.5*RHO*L5/S)
      YDDD=(-0.0005)*(.5*RHO*L2*S**2)
C   YUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED FOR
C   DIFFERENT ENCOUNTER ANGLE , SPEED , ENCOUNTER FREQUENCY
C
C     YVDOT=(-0.0039)*(.5*RHO*L3)
C   SPEED=23 KNOTS,ENCOUNTER ANGLE=60,ENCOUNTER FREQ=0.75
C     YVDOT=-.30908D+07
C     YV=-.81271D+04
C     YVDOT=-.36185D+07
C     YV=-.24757D+06
C     YVDOT=-.32890D+07
C     YV=-.11775D+07
C     YVDOT=-.23038D+07
C     YV=-.18267D+07
      YVDOT=-.59800D+06
      YV=-.13260D+07
C   MOMENT ABOUT Z-AXIS HYDRODYNAMIC COEFFICIENTS (YAW)
      NV=(-0.00213)*(.5*RHO*L3*S)
C     NR=(-0.00105)*(.5*RHO*L4*S)
      ND=(-0.0007)*(.5*RHO*L3*S**2)
      NVVR=(-0.015)*(.5*RHO*L4/S)
      NVRR=(-0.008)*(.5*RHO*L5/S)
      NVVV=(0.01)*(.5*RHO*L3/S)
      NRRR=(-0.006)*(.5*RHO*L6/S)
      NDDD=(0.0001)*(.5*RHO*L3*S**2)
C   NRDOT IS THE ADDED INERTIA TERM WHICH MUST BE CHANGED
C   FOR DIFFERENT ENCOUNTER ANGLE,SPEED,ENCOUNTER FREQUENCY
C
C     NRDOT=(-0.00027)*(.5*RHO*L5)
```

```
C  SPEED=23 KNOTS,ENCOUNTER ANGLE=60,ENCOUNTER FREQ=0.75
C     NRDOT=-.26251D+12
C     NR=-.53637D+09
C     NRDOT=-.20125D+12
C     NR=-.94970D+10
C     NRDOT=-.18671D+12
C     NR=-.46860D+11
C     NRDOT=-.14518D+12
C     NR=-.87538D+11
      NRDOT=-.37261D+11
      NR=-.69856D+11
C  REGULAR WAVE SEA STATE
      FX=WA*RX*DCOS(WE*TIME+TX)
      FY=WA*RY*DCOS(WE*TIME+TY)
      MZ=WA*RZ*DCOS(WE*TIME+TZ)
C  U ACTUAL SPEED
C  UC COMMANDED SPEED
C  XP = PROPELLER THRUST
      XP=-XUU*UC**2
C  EQUATIONS OF MOTION
C     UDOT=( (XVR + MASS)*V*R + XUU*U**2 + XVV*V**2
C    1 + XDD*D*D +  FX + XP )/(MASS-XUDOT)
      VDOT=(YV*V + (YR-MASS*U)*R + YD*D + YVVR*V**2*R
     1 + YVRR*V*R**2 + YVVV*V**3
     2 + YRRR*R**3 + YDDD*D**3 + FY )/(MASS-YVDOT)
      RDOT=(NV*V + NR*R + ND*D + NVVR*V**2*R + NVRR*V*R**2
     1 + NVVV*V**3 + NRRR*R**3 + NDDD*D**3 + MZ)/(IZ-NRDOT)
C  WHEN TO PRINTOUT
      IF (ICOUNT.EQ.11) GO TO 50
      GO TO 300
C  CONVERT RADIANS TO DEGREES
   50 YAWDEG= YAW*57.296
      RDEG=R*57.296
      RDDEG=RDOT*57.296
      DDEG=D*57.296
```

```
      YAWC=YAWC*57.296
      ICOUNT=1
C  TEST IF WANT TO STOP
 300  IF (TIME.GE.ETIME) GO TO 400
C  INTEGRATION STEP SIZE DELT
      DELT=1.0
C  INTEGRATION
      U=U+UDOT*DELT
      V=V+VDOT*DELT
      R=R+RDOT*DELT
      YAW=YAW+R*DELT
      X2=X2+DX2*DELT
C  CONVERT SHIP TO FIXED COORDINATES ON EARTH
C     XDOT=U*DCOS(YAW)-V*DSIN(YAW)
C     YDOT=U*DSIN(YAW)+V*DCOS(YAW)
C     X=X+XDOT*DELT
C     Y=Y+YDOT*DELT
      TIME=TIME+DELT
      ICOUNT=ICOUNT+1
      ISE=ISE + LAMDA*YAWE**2
      ISR=ISR + D**2
      GO TO 200
C  J=TDIFF= COST FUNCTION
 400  TDIFF=ISE+ISR
      WRITE(6,500) ISE,ISR,TDIFF,K1,T1,T2
 500  FORMAT(' ',1X,'ISE=',F15.7,'  ISR=',F15.7,'  TOTAL=',
     1F15.7,2X, 'K1=',F15.7,2X,'T1=',F15.7,2X,'T2=',F15.7)
      RETURN
      END
```

The function minimization subroutine BOXPLX follows.
Then the following two cards must be placed.

```
//GO.SYSIN DD *
/*
```

APPENDIX C

SYSTEM'S RESPONSE FOR REGULAR SEAS

```
//REGURESP JOB (XXXX,XXXX),'RESEARCH',CLASS=A
//*MAIN ORG=NPGVM1.XXXXP
// EXEC FORTXCG,PARM.FORT='OPT(2)',IMSL=DP,REGION=1024K
//FORT.SYSIN DD *
C  IN ORDER TO PERFORM SIMULATION ONLY WHEN GAINS HAVE BEEN
C  OBTAINED CHANGE XS(*) TO X(*) AND DELETE XU(*),AND XL(*)
         COMMON J
         DIMENSION X(3)
         X(1)=1.5420017
         X(2)=141.2350922
         X(3)=23.8943634
C  CALL PLANT(X)
C  IF ONLY SIMULATION IS WANTED
       CALL PLANT(X)
       WRITE (6,25)
 25    FORMAT(1X,' OPTIMAL GAINS',/)
       DO 30 I=1,3
 30    WRITE(6,40)I,X(I)
 40    FORMAT(1X,'X(',I2,')=',F14.7)
       WRITE(6,50) J
50    FORMAT(1X,'J = ',E15.10)
       STOP
       END
       SUBROUTINE PLANT(XX)
C  SUBROUTINE PLANT(XX) SIMULATES THE SHIP
      COMMON TDIFF
      REAL*8 L,L2,L3,L4,L5,L6
      REAL*8 X,XDOT,Y,YDOT,U,UDOT,V,VDOT,YAW,R,RDOT
      REAL*8 TIME,ETIME,XUDOT,XUU,XVR,XVV,XDD
      REAL*8 YV,YR,YD,YVVR,YVRR,YVVV,YRRR,YDDD,YVDOT
```

```
      REAL*8 NV,NR,ND,NVVR,NVRR,NVVV,NRRR,NDDD,NRDOT
      REAL*8 RHO,IZ,FX,FY,MZ,XP,MASS,DELT,MZI,WA,WE
      REAL*8 DYAWE,YAWE,YAWC,ISE,ISR,LAMDA,D,RYR,RYI,MZR
      REAL*8 K1,T1,T2,D,X2,DX2,S,RX,RY,RZ,TX,TY,TZ,RXR,RXI
      DIMENSION XX(3)
C
C  CLOSE LOOP ANALYSIS WITH FILTER
C
C  INITIAL CONDITIONS FOR INTEGRATION
C  SIMULATION END TIME IN SECONDS
      ETIME=600.
      TIME=0.0
      ICOUNT=1
C  INITIALIZE THE COST FUNCTION
      ISE=0.0
      ISR=0.0
      TDIFF=0.0
      LAMDA=8.128
C  GAIN COEFFICIENTS TO BE OPTIMIZED
      K1=XX(1)
      T1=XX(2)
      T2=XX(3)
C     WRITE(6,1010) K1,T1,T2
C1010  FORMAT(1X,'K1 =',F15.7,' T1 =',F15.7,' T2 =',F15.7)
C  X,XDOT,Y,YDOT ARE FIX COORDINATES ON EARTH
      X=0.0
      Y=0.0
      XDOT=0.0
      YDOT=0.0
C  U,UDOT,V,VDOT ARE FIX COORDINATES ON SHIP
      V=0.0
      UDOT=0.0
      VDOT=0.0
      YAW=0.0
      R=0.0
```

```
      RDOT=0.0
C  ORDERED SPEED IN  FEET/SEC
C   38.82 FT/SEC=23 KNOTS
      UC=38.82
C  AT STEADY STATE ACTUAL SPEED (U) = COMMAND SPEED (UC)
      U=UC
C  D = RUDDER ANGLE
      D=0.0
      L=880.5
      L2=L**2
      L3=L*L*L
      L4=L*L3
      L5=L*L4
      L6=L*L5
C  SEA DISTURBANCE
C  FORCES IN X,Y DIRECTION COMPUTED IN FORCES
C  MOMENTS IN Z
      FX=0.
      FY=0.
      MZ=0.
      RXR=-.91037D+03
      RXI=0.50896D+05
      RYR=-.20256D+04
      RYI=.18077D+06
      MZR=-.14310D+08
      MZI=-.16903D+07
      RX=DSQRT(RXR**2+RXI**2)
      RY=DSQRT(RYR**2+RYI**2)
      RZ=DSQRT(MZR**2+MZI**2)
      TX=DATAN2(RXI,RXR)
      TY=DATAN2(RYI,RYR)
      TZ=DATAN2(MZI,MZR)
C  SIGNIFICANT WAVE HEIGHT; SEA STATE 1-0.32,2-0.75,3-2.5,
C  4-5.0,5-7.5,6-10.0,7-17.5,8-20.5,9-27.0
      WA=27.0
```

```
C  ENCOUNTER FREQUENCY .1,.2,.3,.4,.5,.6,.75,1.0,1.5,2.5
      WE=0.2
C  HYDRODYNAMIC COEFFICIENTS ARE INSERTED AS PARAMETERS
      RHO=1.9876
      MASS=(.0044)*(.5*RHO*L3)
      IZ=(0.00028)*(.5*RHO*L5)
      YAWE=0.0
      X2=0.0
      DX2=0.0
  200 CONTINUE
      S=DSQRT(U**2+V**2)
C  INPUT YAW COMMAND
      YAWC=0.0
      IF (TIME.GE.0.0) YAWC=0.0
C  ERROR SIGNAL TO DRIVE RUDDER(YAW ACTUAL - YAW ORDERED)
C  ( COMPENSATOR FILTER )
      YAWE=YAW - YAWC
      DX2=(YAWE-X2)/T2
      D=K1*(T1*DX2+X2)
C  AXIAL FORCE HYDRODYNAMIC COEFFICIENTS (SURGE)
C  XUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED FOR
C  DIFFERENT ENCOUNTER ANGLE , SPEED , ENCOUNTER FREQUENCY
C
      XUDOT=(-.0001)*(.5*RHO*L3)
      XU=(-0.0253)*(.5*RHO*L2*S)
      XUU=(-0.0003)*(.5*RHO*L2)
      XVR=(0.0039)*(.5*RHO*L3)
      XVV=(-.0012)*(.5*RHO*L2)
      XDD=(-0.0005)*(.5*RHO*L2*S**2)
C  LATERAL FORCE HYDRODYNAMIC COEFFICIENTS (SWAY)
C     YV=(-0.00758)*(.5*RHO*L2*S)
      YR=(0.0023)*(.5*RHO*L3*S)
      YD=(0.00145)*(.5*RHO*L2*S**2)
      YVVR=(0.01)*(.5*RHO*L3/S)
      YVRR=(-0.008)*(.5*RHO*L4/S)
```

```
      YVVV=(-0.03)*(.5*RHO*L2/S)
      YRRR=(0.003)*(.5*RHO*L5/S)
      YDDD=(-0.0005)*(.5*RHO*L2*S**2)
C  YUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED FOR
C  DIFFERENT ENCOUNTER ANGLE , SPEED , ENCOUNTER FREQUENCY
C
C     YVDOT=(-0.0039)*(.5*RHO*L3)
C  SPEED=23 KNOTS,ENCOUNTER ANGLE=60,ENCOUNTER FREQ=0.75
      YVDOT=-.30908+07
      YV=-0.81271D+04
C  MOMENT ABOUT Z-AXIS HYDRODYNAMIC COEFFICIENTS (YAW)
      NV=(-0.00213)*(.5*RHO*L3*S)
C     NR=(-0.00105)*(.5*RHO*L4*S)
      ND=(-0.0007)*(.5*RHO*L3*S**2)
      NVVR=(-0.015)*(.5*RHO*L4/S)
      NVRR=(-0.008)*(.5*RHO*L5/S)
      NVVV=(0.01)*(.5*RHO*L3/S)
      NRRR=(-0.006)*(.5*RHO*L6/S)
      NDDD=(0.0001)*(.5*RHO*L3*S**2)
C  NRDOT IS THE ADDED INERTIA TERM WHICH MUST BE CHANGED
C  FOR DIFFERENT ENCOUNTER ANGLE,SPEED,ENCOUNTER FREQUENCY
C
C     NRDOT=(-0.00027)*(.5*RHO*L5)
C  SPEED=32 KNOTS,ENCOUNTER ANGLE=60,ENCOUNTER FREQ=0.75
      NRDOT=-0.26251D+12
      NR=-0.53637D+09
C  REGULAR WAVE SEA STATE
      FX=WA*RX*DCOS(WE*TIME+TX)
      FY=WA*RY*DCOS(WE*TIME+TY)
      MZ=WA*RZ*DCOS(WE*TIME+TZ)
C  U ACTUAL SPEED
C  UC COMMANDED SPEED
C  XP = PROPELLER THRUST
      XP=-XUU*UC**2
C  EQUATIONS OF MOTION
```

```
C     UDOT=( (XVR + MASS)*V*R + XUU*U**2 + XVV*V**2
C    1 + XDD*D*D +  FX. + XP )/(MASS-XUDOT)
      VDOT=(YV*V + (YR-MASS*U)*R + YD*D + YVVR*V**2*R
     1 + YVRR*V*R**2 + YVVV*V**3
     2 + YRRR*R**3 + YDDD*D**3 + FY )/(MASS-YVDOT)
      RDOT=(NV*V + NR*R + ND*D + NVVR*V**2*R + NVRR*V*R**2
     1 + NVVV*V**3 + NRRR*R**3 + NDDD*D**3 + MZ)/(IZ-NRDOT)
C  WHEN TO PRINTOUT
      IF (ICOUNT.EQ. 2) GO TO 50
      GO TO 300
C  CONVERT RADIANS TO DEGREES
  50  YAWDEG= YAW*57.296
      RDEG=R*57.296
      RDDEG=RDOT*57.296
      DDEG=D*57.296
      YAWC=YAWC*57.296
      WRITE (6,101) TIME,YAWDEG
 101  FORMAT(1X,F12.8,1X,F12.8)
      ICOUNT=1
C  TEST IF WANT TO STOP
 300  IF (TIME.GE.ETIME) GO TO 400
C  INTEGRATION STEP SIZE DELT
      DELT=1.0
C  INTEGRATION
      U=U+UDOT*DELT
      V=V+VDOT*DELT
      R=R+RDOT*DELT
      YAW=YAW+R*DELT
      X2=X2+DX2*DELT
C  CONVERT SHIP TO FIXED COORDINATES ON EARTH
C     XDOT=U*DCOS(YAW)-V*DSIN(YAW)
C     YDOT=U*DSIN(YAW)+V*DCOS(YAW)
C     X=X+XDOT*DELT
C     Y=Y+YDOT*DELT
      TIME=TIME+DELT
```

```
      ICOUNT=ICOUNT+1
      ISE=ISE + LAMDA*YAWE**2
      ISR=ISR + D**2
      GO TO 200
C  J=TDIFF= COST FUNCTION
 400  TDIFF=ISE+ISR
      WRITE(6,500) ISE,ISR,TDIFF,K1,T1,T2
 500  FORMAT(' ',1X,'ISE=',F15.7,'  ISR=',F15.7,'  TOTAL=',
     1 F15.7,2X,'K1=',F15.7,2X,'T1=',F15.7,2X,'T2=',F15.7)
      RETURN
      END
//GO.SYSIN DD *
/*
```

APPENDIX D

IRREGULAR SEASTATE FORMULATION

```
//IRREGAINS JOB (XXXX,XXXX),'RESEARCH',CLASS=C
//*MAIN ORG=NPGVM1.XXXXP
// EXEC FORTXCG,PARM.FORT='OPT(2)',IMSL=DP,REGION=1024K
//FORT.SYSIN DD *
C  IN ORDER TO PERFORM SIMULATION ONLY WHEN GAINS HAVE BEEN
C  OBTAINED CHANGE XS(*) TO X(*) AND DELETE XU(*),AND XL(*)
         DIMENSION XS(3),XU(3),XL(3)
         XS(1)=0.655751
         XS(2)=90.5483
         XS(3)=36.74847
C  XS(I) IS THE STARTING GUESS
C  XL(I) IS THE LOWER LIMIT FOR THE I'TH VARIABLE
C  XU(I) IS THE UPPER LIMIT FOR THE I'TH VARIABLE
         XL(1)=0.01
         XU(1)=2.0
         XL(2)=20.0
         XU(2)=180.0
         XL(3)=5.0
         XU(3)=180.0
C  A DESCRIPTION OF THE FOLLOWING PARAMETERS
C  IS DISCUSSED IN BOXPLX
       R=9./13.
       NTA=1000
       NPR=100
       NAV=0
       NV=3
       IP=0
C  THE FOLLOWING STATEMENT MUST BE CHANGED TO
C  CALL PLANT(X)
C  IF ONLY SIMULATION IS WANTED
```

```
      CALL BOXPLX(NV,NAV,NPR,NTA,R,XS,IP,XU,XL,YMN,IER)
      WRITE (6,25)
25    FORMAT(1X,' OPTIMAL GAINS',/)
      DO 30 I=1,3
30    WRITE(6,40)I,XS(I)
40    FORMAT(1X,'X(',I2,')=',F14.7)
      STOP
      END
      SUBROUTINE PLANT(XX)
C  SUBROUTINE PLANT(XX) SIMULATES THE SHIP
      COMMON TDIFF
      REAL*8 L,L2,L3,L4,L5,L6
      REAL*8 X,XDOT,Y,YDOT,U,UDOT,V,VDOT,YAW,R,RDOT
      REAL*8 TIME,ETIME,XUDOT,XUU,XVR,XVV,XDD
      REAL*8 YV,YR,YD,YVVR,YVRR,YVVV,YRRR,YDDD,YVDOT
      REAL*8 NV,NR,ND,NVVR,NVRR,NVVV,NRRR,NDDD,NRDOT
      REAL*8 RHO,IZ,FX,FY,MZ,XP,MASS,DELT
      REAL*8 DYAWE,YAWE,YAWC,ISE,ISR,LAMDA,D
      REAL*8 K1,T1,T2,T3,T4,D,X2,DX2,X3,DX3,X4,CH(11),S
      DIMENSION XX(3)
C
C  CLOSE LOOP ANALYSIS WITH FILTER
C
C  INITIAL CONDITIONS FOR INTEGRATION
C  SIMULATION END TIME IN SECONDS
      ETIME=600.
      TIME=0.0
      ICOUNT=1
C  INITIALIZE THE COST FUNCTION
      ISE=0.0
      ISR=0.0
      TDIFF=0.0
      LAMDA=8.128
C  GAIN COEFFICIENTS TO BE OPTIMIZED
      K1=XX(1)
```

```
      T1=XX(2)
      T2=XX(3)
C     WRITE(6,1010) K1,T1,T2
C  X,XDOT,Y,YDOT ARE FIX COORDINATES ON EARTH
      X=0.0
      Y=0.0
      XDOT=0.0
      YDOT=0.0
C  U,UDOT,V,VDOT ARE FIX COORDINATES ON SHIP
      V=0.0
      UDOT=0.0
      VDOT=0.0
      YAW=0.0
      R=0.0
      RDOT=0.0
C  ORDERED SPEED IN  FEET/SEC
C   38.82 FT/SEC=23 KNOTS
      UC=38.82
C  AT STEADY STATE ACTUAL SPEED (U) = COMMAND SPEED (UC)
      U=UC
C  D = RUDDER ANGLE
      D=0.0
      L=880.5
      L2=L**2
      L3=L*L*L
      L4=L*L3
      L5=L*L4
      L6=L*L5
C  SEA DISTURBANCE
C  FORCES IN X,Y DIRECTION COMPUTED IN FORCES
C  MOMENTS IN Z
      FX=0.
      FY=0.
      MZ=0.
C  ISEA IS A SWITCH ;ISEA=0 (CALM WATER) ISEA=1 (SEA STATE)
```

```
      ISEA=1
C  HYDRODYNAMIC COEFFICIENTS ARE INSERTED AS PARAMETERS
      RHO=1.9876
      MASS=(.0044)*(.5*RHO*L3)
      IZ=(0.00028)*(.5*RHO*L5)
      YAWE=0.0
      X2=0.0
      DX2=0.0
  200 CONTINUE
      S=DSQRT(U**2+V**2)
C  INPUT YAW COMMAND
      YAWC=0.0
      IF (TIME.GE.0.0) YAWC=0.0
C  ERROR SIGNAL TO DRIVE RUDDER(YAW ACTUAL - YAW ORDERED)
C  ( CONTROLLER  FILTER )
      YAWE=YAW - YAWC
      DX2=(YAWE-X2)/T2
      D=K1*(T1*DX2+X2)
C  AXIAL FORCE HYDRODYNAMIC COEFFICIENTS (SURGE)
C  XUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED FOR
C  DIFFERENT ENCOUNTER ANGLE , SPEED , ENCOUNTER FREQUENCY
C
      XUDOT=(-.0001)*(.5*RHO*L3)
      XU=(-0.0253)*(.5*RHO*L2*S)
      XUU=(-0.0003)*(.5*RHO*L2)
      XVR=(0.0039)*(.5*RHO*L3)
      XVV=(-.0012)*(.5*RHO*L2)
      XDD=(-0.0005)*(.5*RHO*L2*S**2)
C  LATERAL FORCE HYDRODYNAMIC COEFFICIENTS (SWAY)
      YV=(-0.00758)*(.5*RHO*L2*S)
      YR=(0.0023)*(.5*RHO*L3*S)
      YD=(0.00145)*(.5*RHO*L2*S**2)
      YVVR=(0.01)*(.5*RHO*L3/S)
      YVRR=(-0.008)*(.5*RHO*L4/S)
      YVVV=(-0.03)*(.5*RHO*L2/S)
```

```
      YRRR=(0.003)*(.5*RHO*L5/S)
      YDDD=(-0.0005)*(.5*RHO*L2*S**2)
C  YUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED FOR
C  DIFFERENT ENCOUNTER ANGLE , SPEED , ENCOUNTER FREQUENCY
C
C     YVDOT=(-0.0039)*(.5*RHO*L3)
C  SPEED=23 KNOTS, ENCOUNTER FREQUENCY =0.75
      YVDOT=-2304300.0
C  MOMENT ABOUT Z-AXIS HYDRODYNAMIC COEFFICIENTS (YAW)
      NV=(-0.00213)*(.5*RHO*L3*S)
      NR=(-0.00105)*(.5*RHO*L4*S)
      ND=(-0.0007)*(.5*RHO*L3*S**2)
      NVVR=(-0.015)*(.5*RHO*L4/S)
      NVRR=(-0.008)*(.5*RHO*L5/S)
      NVVV=(0.01)*(.5*RHO*L3/S)
      NRRR=(-0.006)*(.5*RHO*L6/S)
      NDDD=(0.0001)*(.5*RHO*L3*S**2)
C  NRDOT IS THE ADDED INERTIA TERM WHICH MUST BE CHANGED
C  FOR DIFFERENT ENCOUNTER ANGLE,SPEED,ENCOUNTER FREQUENCY
C
C     NRDOT=(-0.00027)*(.5*RHO*L5)
C  SPEED=23 KNOTS, ENCOUNTER FREQUENCY =0.75
      NRDOT=-1.4518E+11
C  SETS SEA STATE TO ZERO
      IF (ISEA.EQ.1) GO TO 30
      FX=0.
      FY=0.
      MZ=0.
     GO TO 35
C  UNIT 12 HAS THE SEA STATE DATA NAMED CH
C  IT MUST BE SYNCHRONIZED BY TIME
 30   READ (12) CH
      FX=CH(3)
      FY=CH(4)
      MZ=CH(8)
```

```
 35   CONTINUE
C  U ACTUAL SPEED
C  UC COMMANDED SPEED
C  XP = PROPELLER THRUST
      XP=-XUU*UC**2
C  EQUATIONS OF MOTION
C     UDOT=( (XVR + MASS)*V*R + XUU*U**2 + XVV*V**2
C    1 + XDD*D*D +  FX + XP )/(MASS-XUDOT)
      VDOT=(YV*V + (YR-MASS*U)*R + YD*D + YVVR*V**2*R
     1 + YVRR*V*R**2 + YVVV*V**3
     2 + YRRR*R**3 + YDDD*D**3 + FY )/(MASS-YVDOT)
      RDOT=(NV*V + NR*R + ND*D + NVVR*V**2*R + NVRR*V*R**2
     1 + NVVV*V**3 + NRRR*R**3 + NDDD*D**3 + MZ)/(IZ-NRDOT)
C  WHEN TO PRINTOUT
      IF (ICOUNT.EQ.11) GO TO 50
      GO TO 300
C  CONVERT RADIANS TO DEGREES
  50  YAWDEG= YAW*57.296
      RDEG=R*57.296
      RDDEG=RDOT*57.296
      DDEG=D*57.296
      YAWC=YAWC*57.296
      ICOUNT=1
C  TEST IF WANT TO STOP
 300  IF (TIME.GE.ETIME) GO TO 400
C  INTEGRATION STEP SIZE DELT
      DELT=1.0
C  INTEGRATION
      U=U+UDOT*DELT
      V=V+VDOT*DELT
      R=R+RDOT*DELT
      YAW=YAW+R*DELT
      X2=X2+DX2*DELT
C  CONVERT SHIP TO FIXED COORDINATES ON EARTH
C     XDOT=U*DCOS(YAW)-V*DSIN(YAW)
```

```
C     YDOT=U*DSIN(YAW)+V*DCOS(YAW)
C     X=X+XDOT*DELT
C     Y=Y+YDOT*DELT
      TIME=TIME+DELT
      ICOUNT=ICOUNT+1
      ISE=ISE + LAMDA*YAWE**2
      ISR=ISR + D**2
      GO TO 200
C  J=TDIFF= COST FUNCTION
 400  TDIFF=ISE+ISR
      WRITE(6,500) TDIFF,K1,T1,T2
 500  FORMAT(' ',1X,'TOTAL =',F15.7,'  K1 =',F15.7,
     1 ' T1 =',F15.7,2X,'T2=',F15.7)
      REWIND 12
      RETURN
      END
```

The function minimization subroutine BOXPLX follows.
Then the following three cards must be placed.

```
//GO.SYSIN DD *
/*
/ GO.FT12F001 DD DISP=SHR,DSN=MSS.S2160.A241
```

APPENDIX E

SYSTEM'S RESPONSE FOR IRREGULAR SEAS

```
//IRRERESP JOB (XXXX,XXXX),'RESEARCH',CLASS=B
//*MAIN ORG=NPGVM1.XXXXP
// EXEC FRTXCLGP,IMSL=DP,REGION=1024K
//FORT.SYSIN DD *
C  IN ORDER TO PERFORM SIMULATION ONLY WHEN GAINS HAVE BEEN
C  OBTAINED
       DIMENSION XX(3)
C  OPTIMAL GAINS FOR CONTROLLER
       XX(1)=.9192610
       XX(2)=18.5788116
       XX(3)=9.77668
C  THE SUBROUTINE PLANT SIMULATES THE SL-7 CONTAINERSHIP
      CALL PLANT(XX)
      WRITE(6,25)
25    FORMAT(1X,'OPTIMAL GAINS',/)
      DO 30 I=1,3
30    WRITE(6,40)I,XX(I)
40    FORMAT(1X,'XX(',I2,')=',F14.7)
      STOP
      END
C
C  SUBROUTINE PLANT(XX)  SIMULATES THE SHIP
      SUBROUTINE PLANT(XX)
      COMMON TDIFF
      REAL*8 L,L2,L3,L4,L5,L6
      REAL*8 X,XDOT,Y,YDOT,U,UDOT,V,VDOT,YAW,R,RDOT
      REAL*8 TIME,ETIME,XUDOT,XUU,XVR,XVV,XDD
      REAL*8 YV,YR,YD,YVVR,YVRR,YVVV,YRRR,YDDD,YVDOT
      REAL*8 NV,NR,ND,NVVR,NVRR,NVVV,NRRR,NDDD,NRDOT
      REAL*8 RHO,IZ,FX,FY,MZ,XP,MASS,DELT
```

```
      REAL*8 DYAWE,YAWE,YAWC,ISE,ISR,LAMDA,D
      REAL*8 K1,T1,T2,D,X2,DX2,S,CH(11),DX3,X3,X4
      DIMENSION XX(3)
C
C  CLOSE LOOP ANALYSIS WITH FILTER
C
   INITIAL CONDITIONS FOR INTEGRATION
C  SIMULATION END TIME IN SECONDS
      ETIME=600.
      TIME=0.0
      ICOUNT=1
C  INITIALIZE THE COST FUNCTION
      ISE=0.0
      ISR=0.0
      TDIFF=0.0
      LAMDA=4.2
C  GAIN COEFFICIENTS
      K1=XX(1)
      T1=XX(2)
      T2=XX(3)
C  X,XDOT,Y,YDOT ARE FIX COORDINATES ON EARTH
      X=0.0
      Y=0.0
      XDOT=0.0
      YDOT=0.0
C  U,UDOT,V,VDOT ARE FIX COORDINATES ON SHIP
      V=0.0
      UDOT=0.0
      VDOT=0.0
      YAW=0.0
      R=0.0
      RDOT=0.0
      YAW=0.0
C  ORDERED SPEED IN  FEET/SEC
C   38.81 FT/SEC=23 KNOTS
```

```
      UC=38.81
C   AT STEADY STATE ACTUAL SPEED (U) = COMMAND SPEED (UC)
      U=UC
C   D = RUDDER ANGLE
      D=0.0
      L=880.5
      L2=L**2
      L3=L*L*L
      L4=L*L3
      L5=L*L4
      L6=L*L5
C   SEA DISTURBANCE
C   FORCES IN X,Y DIRECTION COMPUTED IN FORCES
C   MOMENTS IN Z
      FX=0.
      FY=0.
      MZ=0.
C   ISEA IS A SWITCH; ISEA=0 (CALM WATER) ISEA=1 (SEA STATE)
      ISEA=1
C   HYDRODYNAMIC COEFFICIENTS ARE INSERTED AS PARAMETERS
      RHO=1.9876
      MASS=(.0044)*(.5*RHO*L3)
      IZ=(0.00028)*(.5*RHO*L5)
      YAWE=0.0
      X2=0.0
      DX2=0.0
      X3=0.0
      DX3=0.0
      X4=0.0
  200 CONTINUE
      S=DSQRT(U**2 + V**2)
C   INPUT YAW COMMAND
      YAWC=0.0
      IF (TIME.GE.0.0) YAWC=0.0
C   ERROR SIGNAL TO DRIVE RUDDER(YAW ACTUAL - YAW ORDERED)
```

```
C  ( COMPENSATOR FILTER )
      YAWE=YAW - YAWC
      DX2=(YAWE-X2)/T2
      X4=K1*(T1*DX2+X2)
      DX3=(X4-X3)/T4
      D=(T3*DX3+X3)
C  AXIAL FORCE HYDRODYNAMIC COEFFICIENTS (SURGE)
C
C  XUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED FOR
C  DIFFERENT ENCOUNTER ANGLE AND SPEED.
C     XUDOT=(-.0001)*(.5*RHO*L3)
      XUU=(-0.0003)*(.5*RHO*L2)
      XVR=(0.0039)*(.5*RHO*L3)
      XVV=(-.0012)*(.5*RHO*L2)
      XDD=(-0.0005)*(.5*RHO*L2*S**2)
C  LATERAL FORCE HYDRODYNAMIC COEFFICIENTS (SWAY)
      YV=(-0.00758)*(.5*RHO*L2*S)
      YR=(0.0023)*(.5*RHO*L3*S)
      YD=(0.00145)*(.5*RHO*L2*S**2)
      YVVR=(0.01)*(.5*RHO*L3/S)
      YVRR=(-0.008)*(.5*RHO*L4/S)
      YVVV=(-0.03)*(.5*RHO*L2/S)
      YRRR=(0.003)*(.5*RHO*L5/S)
      YDDD=(-0.0005)*(.5*RHO*L2*S**2)
C  YUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED FOR
C  DIFFERENT ENCOUNTER ANGLE AND SPEED.
C
C     YVDOT=(-0.0039)*(.5*RHO*L3)
      YVDOT=-3654800.00
C  MOMENT ABOUT Z-AXIS HYDRODYNAMIC COEFFICIENTS (YAW)
      NV=(-0.00213)*(.5*RHO*L3*S)
      NR=(-0.00105)*(.5*RHO*L4*S)
      ND=(-0.0007)*(.5*RHO*L3*S**2)
      NVVR=(-0.015)*(.5*RHO*L4/S)
      NVRR=(-0.008)*(.5*RHO*L5/S)
```

```
      NVVV=(0.01)*(.5*RHO*L3/S)
      NRRR=(-0.006)*(.5*RHO*L6/S)
      NDDD=(0.0001)*(.5*RHO*L3*S**2)
C  NRDOT IS THE ADDED INERTIA TERM WHICH MUST BE CHANGED
C  FOR DIFFERENT ENCOUNTER ANGLE AND SPEED.
C
C     NRDOT=(-0.00027)*(.5*RHO*L5)
      NRDOT=-2.1815E+11
C  SETS SEA STATE TO ZERO
      IF (ISEA.EQ.1) GO TO 30
      FX=0.
      FY=0.
      MZ=0.
      GO TO 35
C  UNIT 12 HAS THE SEA STATE DATA NAMED CH
C  IT MUST BE SYNCHRONIZED BY TIME
 30    READ (12) CH
       FX= CH(3)
       FY= CH(4)
       MZ= CH(8)
 35    CONTINUE
C  U ACTUAL SPEED
C  UC COMMANDED SPEED
C  XP = PROPELLER THRUST
      XP=-XUU*UC**2
C  EQUATIONS OF MOTION
C     UDOT=( (XVR + MASS)*V*R + XUU*U**2 + XVV*V**2
C    1 + XDD*D*D + FX  + XP )/(MASS-XUDOT)
      VDOT=(YV*V + (YR-MASS*S)*R + YD*D + YVVR*V**2*R
     1 + YVRR*V*R**2 + YVVV*V**3
     1 + YRRR*R**3 + YDDD*D**3 + FY )/(MASS-YVDOT)
      RDOT=(NV*V + NR*R + ND*D + NVVR*V**2*R + NVRR*V*R**2
     1 + NVVV*V**3 + NRRR*R**3 + NDDD*D**3 + MZ)/(IZ-NRDOT)
C  WHEN TO PRINTOUT
      IF (ICOUNT.EQ.2 ) GO TO 50
```

```
      GO TO 300
C  CONVERT RADIANS TO DEGREES
  50  YAWDEG= YAW*57.296
      RDEG=R*57.296
      RDDEG=RDOT*57.296
      DDEG=D*57.296
      YAWC=YAWC*57.296
      WRITE (6,100) TIME,YAWDEG
  100 FORMAT(1X,F12.8,1X,F12.8)
      ICOUNT=1
C  TEST IF WANT TO STOP
 300  IF (TIME.GE.ETIME) GO TO 400
C  INTEGRATION STEP SIZE DELT
      DELT=1.
C  INTEGRATION
      U=U+UDOT*DELT
      V=V+VDOT*DELT
      R=R+RDOT*DELT
      YAW=YAW+R*DELT
      X2=X2+DX2*DELT
      X3=X3+DX3*DELT
C  CONVERT SHIP TO FIXED COORDINATES ON EARTH
      XDOT=U*DCOS(YAW)-V*DSIN(YAW)
      YDOT=U*DSIN(YAW)+V*DCOS(YAW)
      X=X+XDOT*DELT
      Y=Y+YDOT*DELT
      TIME=TIME+DELT
      ICOUNT=ICOUNT+1
      ISE=ISE + LAMDA*YAWE**2
      ISR=ISR + D**2
      GO TO 200
C  J=TDIFF= COST FUNCTION
 400  TDIFF=ISE+ISR
      WRITE(6,500) ISE,ISR,TDIFF
 500  FORMAT('1',5X,'ISE=',F15.7,'  ISR=',F15.7,
```

```
     1 ' TOTAL=',F15.7)
      STOP
      END
//GO.SYSIN DD *
/*
//GO.FT12F001 DD DISP=SHR,DSN=MSS.S2160.A211
```

APPENDIX F

MODIFIED MINIMIZATION SUBROUTINE

```
      SUBROUTINE BOXPLX (NV,NAV,NPR,NTZ,RZ,XS,IP,BU,BL,YMN,IER)
C
      DIMENSION V(50,50), FUN(50), SUM(25), CEN(25), XS(NV),
     1BU(NV),BL(NV)
C
        KV = 5
        EP = 1.E-4
        NTA = 2000
        IF (NTZ.GT.0) NTA = NTZ
        R = RZ
        IF (R.LE.0..OR.R.GE.1.) R=1./3.
        NVT = NV+NAV
C
C       TOTAL VARS, EXPLICIT PLUS IMPLICIT
        NT = 0
C       CURRENT TRIAL NO.
        NPT = 0
C       CURRENT NO. OF PERMISSIBLE TRIALS
        NTFS = 0
C       CURRENT NO. OF TIMES F HAS BEEN ALMOST UNCHANGED
C
C       CHECK FEASIBILITY OF START POINT
C
        DO 4 I=1,NV
        VT = XS(I)
        IF (BL(I).LE.VT) GO TO 1
        II = -I
        VT = BL(I)
        GO TO 2
      1 IF (BU(I).GE.VT) GO TO 3
```

```
      II = I
      VT = BU(I)
    2 IF (NPR.GT.0) WRITE (6,49) II
    3 V(I,1) = VT
      CEN(I) = VT
      IF (IP.EQ.1) GO TO 4
      BL(I) = BL(I)+AMAX1(EP,EP*ABS(BL(I)))
      BU(I) = BU(I)-AMAX1(EP,EP*ABS(BU(I)))
    4 SUM(I) = VT
C
C
      NCE = 1
C     NUMBER OF CONSTRAINT EVALUATIONS
      I = 1
      IF (KE(V(1,1)).EQ.0) GO TO 5
      IF (NPR.LE.0) GO TO 12
      WRITE (6,50)
      GO TO 12
    5 NFE = 1
C
C    NUMBER OF VERTICES (K) = 2 TIMES NO. OF VARIABLES.
      K = (2*NV)/3
C
C    NUMBER OF DISPLACEMENTS ALLOWED.
      NLIM = 5*NV+10
C
C    NUMBER OF CONSECUTIVE TRIALS WITH UNCHANGED FE TO
C    TO TERMINATE
      NCT = NLIM+NV
      ALPHA = 1.3
      FK = K
      FKM = FK-1.
      BETA = ALPHA+1.
C
C    INSURE SEED OF RANDOM NUMBER GENERATOR IS ODD.
```

```
      IQR = R*1.E7
      IF (MOD(IQR,2).EQ.0) IQR=IQR+101
C
C     SET UP INITIAL VERTICES
      FUN(1) = FE(V(1,1))
      YMN = FUN(1)
    6 FI = 1.
      FUNOLD = FUN(1)
C
      DO 15 I=2,K
      FI = FI+1.
      LIMT = 0
    7 LIMT = LIMT+1
C
C    END CALCULATION IF FEASIBLE CENTROID CANNOT BE FOUND.
      IF (LIMT.GE.NLIM) GO TO 11
C
      DO 8 J=1,NV
C
C    RANDOM NUMBER GENERATOR  (RANDU)
      IQR = IQR*65539
      IF (IQR.LT.0) IQR = IQR+2147483647+1
      RQX = IQR
      RQX = RQX*.4656613E-9
      V(J,I) = BL(J)+RQX*(BU(J)-BL(J))
      IF (IP.EQ.1) V(J,I)=AINT(V(J,I)+.5)
    8 CONTINUE
C
      DO 10 L=1,NLIM
      NCE = NCE+1
      IF (KE(V(1,I)).EQ.0) GO TO 13
C
      DO 9 J=1,NV
      VT = .5*(V(J,I)+CEN(J))
      IF (IP.EQ.1) VT = AINT(VT+.5)
```

```
      V(J,I) = VT
    9 CONTINUE
C
   10 CONTINUE
C
   11 IF (NPR.LE.0) GO TO 12
      WRITE (6,51) I
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,I,FUN,CEN,I)
   12 IER = -1
      GO TO 48
C
   13 DO 14 J=1,NV
      SUM(J) = SUM(J)+V(J,I)
   14 CEN(J) = SUM(J)/FI
C
C     TRY TO ASSURE FEASIBLE CENTROID FOR STARTING.
      NCE = NCE+1
      IF (KE(CEN).EQ.0) GO TO 60
      SUM(J) = SUM(J) -V(J,I)
      GO TO 7
   60 NFE = NFE+1
      FUN(I) = FE(V(1,I))
   15 CONTINUE
C
C     END OF LOOP SETTING OF INITIAL COMPLEX.
      IF (NPR.LE.0) GO TO 17
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,0)
C
C     FIND THE WORST VERTEX, THE 'J'TH.
      J = 1
C
      DO 16 I=2,K
      IF (FUN(J).GE.FUN(I)) GO TO 16
      J = I
   16 CONTINUE
```

```
C
C   BASIC LOOP.  ELIMINATE EACH WORST VERTEX IN TURN.
C   IT MUST BECOME NO LONGER WORST, NOT MERELY IMPROVED.
C   FIND NEXT-TO-WORST VERTEX,  THE 'JN'TH ONE.
  17 JN = 1
     IF (J.EQ.1) JN = 2
C
     DO 18 I=1,K
     IF (I.EQ.J) GO TO 18
     IF (FUN(JN).GE.FUN(I)) GO TO 18
     JN = I
  18 CONTINUE
C
C   LIMT = NUMBER OF MOVES DURING THIS TRIAL TOWARD THE
C   CENTROID DUE TO FUNCTION VALUE.
     LIMT = 1
C
C   COMPUTE CENTROID AND OVER REFLECT WORST VERTEX.
C
     DO 19 I=1,NV
     VT = V(I,J)
     SUM(I) = SUM(I)-VT
     CEN(I) = SUM(I)/FKM
     VT = BETA*CEN(I)-ALPHA*VT
     IF (IP.EQ.1) VT = AINT(VT+.5)
C
C   INSURE THE EXPLICIT CONSTRAINTS ARE OBSERVED.
  19 V(I,J) = AMAX1(AMIN1(VT,BU(I)),BL(I))
C
     NT = NT+1
C
C   CHECK FOR IMPLICIT CONSTRAINT VIOLATION.
C
  20 DO 25 N=1,NLIM
     NCE = NCE+1
```

```
      IF (KE(V(1,J)).EQ.0) GO TO 26
C
C     EVERY 'KV'TH TIME, OVER-REFLECT THE OFFENDING VERTEX
C     THROUGH THE BEST VERTEX.
      IF (MOD(N,KV).NE.0) GO TO 22
      CALL FBV (K,FUN,M)
C
      DO 21 I=1,NV
      VT = BETA*V(I,M)-ALPHA*V(I,J)
      IF (IP.EQ.1) VT = AINT(VT+.5)
   21 V(I,J) = AMAX1(AMIN1(VT,BU(I)),BL(I))
C
      GO TO 24
C
C     CONSTRAINT VIOLATION:  MOVE NEW POINT TOWARD CENTROID.
C
   22 DO 23 I=1,NV
      VT = .5*(CEN(I)+V(I,J))
      IF (IP.EQ.1) VT = AINT(VT+.5)
      V(I,J) = VT
   23 CONTINUE
C
   24 NT = NT+1
   25 CONTINUE
C
      IER = 1
C
C     CANNOT GET FEASIBLE VERTEX BY MOVING TOWARD CENTROID,
C     OR BY OVER-REFLECTING THRU THE BEST VERTEX.
      IF (NPR.LE.0) GO TO 42
      WRITE (6,52) NT,J
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,J)
      GO TO 42
C
C     FEASIBLE VERTEX FOUND, EVALUATE THE OBJECTIVE FUNCTION.
```

```
   26 NFE = NFE+1
      FUNTRY = FE(V(1,J))
C
C   TEST TO SEE IF FUNCTION VALUE HAS NOT CHANGED.
      AFO = ABS(FUNTRY-FUNOLD)
      AMX = AMAX1(ABS(EP*FUNOLD),EP)
C
C   ACTIVATE THE FOLLOWING TWO STATEMENTS
C   FOR DIAGNOSTIC PURPOSES ONLY.
C     WRITE (6,99) J,AFO,AMX,FUNTRY,FUNOLD,FUN(J),FUN(JN),
C    1NTFS,N
C  99 FORMAT (1X,I3,6E15.7,2I5)
      IF (AFO.GT.AMX) GO TO 27
      NTFS = NTFS+1
      IF (NTFS.LT.NCT) GO TO 28
      IER = 0
      IF (NPR.LE.0) GO TO 42
      WRITE (6,53) K
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,0)
      GO TO 42
   27 NTFS = 0
C
C   IS THE NEW VERTEX NO LONGER WORST?
   28 IF (FUNTRY.LT.FUN(JN)) GO TO 34
C
C   TRIAL VERTEX IS STILL WORST; ADJUST TOWARD CENTROID.
C   EVERY 'KV'TH TIME, OVER-REFLECT THE OFFENDING VERTEX
C   THROUGH THE BEST VERTEX.
      LIMT = LIMT+1
      IF (MOD(LIMT,KV).NE.0) GO TO 30
      CALL FBV (K,FUN,M)
C
      DO 29 I=1,NV
      VT = BETA*V(I,M)-ALPHA*V(I,J)
      IF (IP.EQ.1) VT = AINT(VT+.5)
```

```
  29 V(I,J) = AMAX1(AMIN1(VT,BU(I)),BL(I))
C
     GO TO 32
C
  30 DO 31 I=1,NV
     VT = .5*(CEN(I)+V(I,J))
     IF (IP.EQ.1) VT = AINT(VT+.5)
     V(I,J) = VT
  31 CONTINUE
C
  32 IF (LIMT.LT.NLIM) GO TO 33
C
C   CANNOT MAKE THE 'J'TH VERTEX NO LONGER WORST BY
C   DISPLACING TOWARD THE CENTROID OR BY OVER-REFLECTING
C   THRU THE BEST VERTEX.
     IER = 2
     IF (NPR .LE. 0)  GO TO 42
     WRITE (6,52)  NT, J
     CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,J)
     GO TO 42
  33 NT = NT+1
     GO TO 20
C
C   SUCCESS:  WE HAVE A REPLACEMENT FOR VERTEX J.
  34 FUN(J) = FUNTRY
     FUNOLD = FUNTRY
     NPT = NPT+1
C
C   STOP AT THE 100'TH PERMISSIBLE TRIAL
     IF (MOD(NPT,100).EQ.0) GO TO 48
C
     DO 36 I=1,NV
     SUM(I) = 0.
C
     DO 35 N=1,K
```

```
   35 SUM(I) = SUM(I)+V(I,N)
C
      CEN(I) = SUM(I)/FK
   36 CONTINUE
C
      LC = 0
      GO TO 39
C
   37 DO 38 I=1,NV
   38 SUM(I) = SUM(I)+V(I,J)
C
      LC = J
C
   39 IF (NPR.LE.0) GO TO 40
      IF (MOD(NPT,NPR).NE.0) GO TO 40
C
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,LC)
C
C    HAS THE MAX. NUMBER OF TRIALS BEEN REACHED WITHOUT
C    CONVERGENCE ? IF NOT, GO TO NEW TRIAL.
   40 IF (NT.GE.NTA) GO TO 41
C
C        NEXT-TO-WORST VERTEX NOW BECOMES WORST.
      J = JN
      GO TO 17
   41 IER = 3
      IF (NPR.GT.0) WRITE (6,54)
C
C    COLLECTOR POINT FOR ALL ENDINGS.
C     1)  CANNOT DEVELOP FEASIBLE VERTEX.             IER = 1
C     2)  CANNOT DEVELOP A NO-LONGER-WORST VERTEX.    IER = 2
C     3)  FUNCTION VALUE UNCHANGED FOR K TRIALS.      IER = 0
C     4)  LIMIT ON TRIALS REACHED.                    IER = 3
C     5)  CANNOT FIND FEASIBLE VERTEX AT START.       IER =-1
   42 CONTINUE
```

```
C
C   FIND BEST VERTEX.
     CALL FBV (K,FUN,M)
     IF (IER.GE.3) GO TO 44
C   RESTART IF THIS SOLUTION IS SIGNIFICANTLY BETTER THAN
C   THE PREVIOUS OR IF THIS IS THE FIRST TRY.
     IF (NPR.LE.0) GO TO 43
     WRITE (6,55) (M,YMN,FUN(M))
  43 IF (FUN(M).GE.YMN) GO TO 47
     IF (ABS(FUN(M)-YMN).LE.AMAX1(EP,EP*YMN)) GO TO 47
C   GIVE IT ANOTHER TRY UNLESS LIMIT ON TRIALS REACHED.
  44 YMN = FUN(M)
     FUN(1) = FUN(M)
C
     DO 45 I=1,NV
     CEN(I) = V(I,M)
     SUM(I) = V(I,M)
  45 V(I,1) = V(I,M)
C
     DO 46 I=1,NVT
  46 XS(I) = V(I,M)
C
     IF (IER.LT.3) GO TO 6
  47 IF (NPR.LE.0) GO TO 48
     CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,V(1,M),-1)
     WRITE (6,56) FUN(M)
  48 RETURN
C
  49 FORMAT (50H0INDEX AND DIRECTION OF OUTLYING
    1VARIABLE AT STARTI5)
  50 FORMAT (50H0IMPLICIT CONSTRAINT VIOLATED AT START.
    1DEAD END.)
  51 FORMAT ('0CANNOT FIND FEASIBLE',I4,'TH VERTEX OR
    1CENTROID AT START.')
  52 FORMAT (10H0AT TRIAL I4,54H CANNOT FIND FEASIBLE
```

```
     1VERTEX WHICH IS NO
     2LONGER WORST,I4,15X,'RESTART FROM BEST VERTEX.')
  53 FORMAT (40H0FUNCTION HAS BEEN ALMOST UNCHANGED
     1FOR I5,7H TRIALS)
  54 FORMAT (27H0LIMIT ON TRIALS EXCEEDED. )
  55 FORMAT ('0BEST VERTEX IS NO.',I3,'  OLD MIN WAS ',
     1E15.7, '  NEW MIN IS ',E15.7)
  56 FORMAT ('0MIN OBJECTIVE FUNCTION IS ',E15.7)
     END
     SUBROUTINE FBV (K,FUN,M)
     DIMENSION FUN(50)
     M = 1
C
     DO 1 I=2,K
     IF (FUN(M).LE.FUN(I)) GO TO 1
     M = I
   1 CONTINUE
C
     RETURN
     END
     SUBROUTINE BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FN,C,IK)
     DIMENSION V(50,50), FN(50), C(25)
     WRITE (6,4) NT,NPT,NFE,NCE
C
     DO 1 I=1,K
     WRITE (6,5) FN(I),(V(J,I),J=1,NV)
     IF (NVT.LE.NV) GO TO 1
     NVP = NV+1
     WRITE (6,6) (V(J,I),J=NVP,NVT)
   1 CONTINUE
C
     IF (IK.NE.0) GO TO 2
C
     WRITE (6,7) (C(I),I=1,NV)
     RETURN
```

```
    2 IF (IK.GE.0) GO TO 3
      WRITE (6,8) (C(I),I=1,NV)
      RETURN
    3 WRITE (6,9) IK,(C(I),I=1,NV)
      RETURN
C
    4 FORMAT ('ONO. TOTAL TRIALS = ',I5,4X,'NO. FEASIBLE
     1TRIALS = ',
     2I5,4X,'NO. FUNCTION EVALUATIONS = ',I5,4X,'NO.
     3CONSTRAINT EVALUATIONS
     4= ',I5/'0     FUNCTION VALUE',6X,'INDEPENDENT
     5VARIABLES/DEPENDENT
     6OR IMPLICIT CONSTRAINTS')
    5 FORMAT (1H ,E18.7,2X,7E14.7/(21X,7E14.7))
    6 FORMAT (21X,7E14.7)
    7 FORMAT (10HOCENTROID 11X,7E14.7/(21X,7E14.7))
    8 FORMAT ('0  BEST VERTEX',7X,7E14.7/(21X,7E14.7))
    9 FORMAT ('OCENTROID LESS VX',I2,2X,7E14.7/(21X,7E14.7))
      END
       FUNCTION FE(X)
       DIMENSION X(3)
       COMMON TDIFF
       CALL PLANT(X)
       FE=TDIFF
       RETURN
       END
       FUNCTION KE(X)
       DIMENSION X(3)
       KE=0
       RETURN
       END
```

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